QCD and neutrinos
or
The particle theory of neutrino-nucleus cross sections

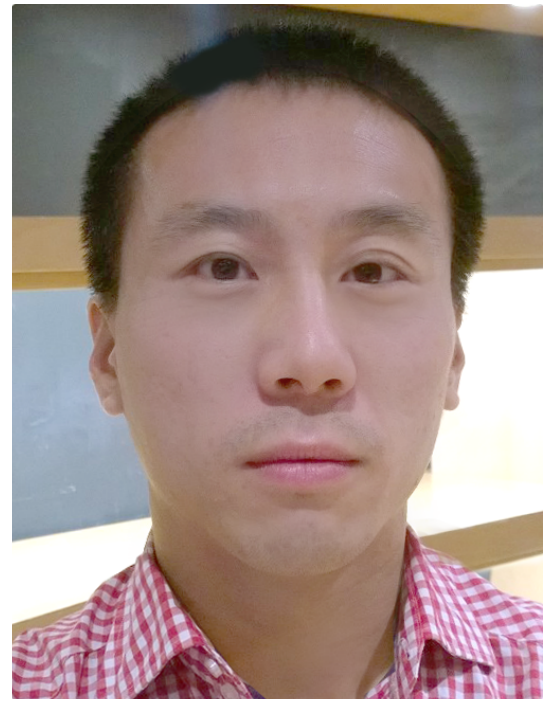
RICHARD HILL

TRIUMF & Perimeter Institute & U. Chicago

Fermilab neutrino division seminar
11 February 2016

Featuring work of the following students

M. Solon,
(2015 Sakurai thesis award
U.Chicago→UC Berkeley/LBNL)



G. Lee
(U.Chicago→Technion
Supported by NIST PMG)

A. Meyer
(U.Chicago/FNAL
DOE SCGSR award)

WIMP-nucleus *electron-proton* *neutrino-nucleus*

Thanks also: J. Arrington, M. Betancourt, C. Blanco, R. Gran, A. Kronfeld, G. Paz, M. Wetstein, and many others.

outline

- the particle physics of neutrino cross sections
  - precision hadron physics and elementary targets
  - radiative corrections
  - lattice QCD
- interplay with nuclear modeling
- interplay with detector technology
- connections with other processes and new physics searches

some new results

• new results from an analysis of neutrino-deuteron scattering *M. Betancourt, R. Gran, RJH, A. Meyer (to appear)*

- nucleon axial radius very different from conventional wisdom

- model independent (z expansion) form factor extracted: *coefficients, errors, correlations*

• all of this built into GENIE: readily integrated with nuclear corrections and errors propagated to neutrino parameters

• further improvement expected from lattice QCD

Have established a new physics scale

$$\frac{1}{\Lambda} HHEE \qquad\qquad \Lambda \sim \frac{v_{\mathrm{weak}}^2}{m_\nu} \sim 10^{14}\,\mathrm{GeV}$$

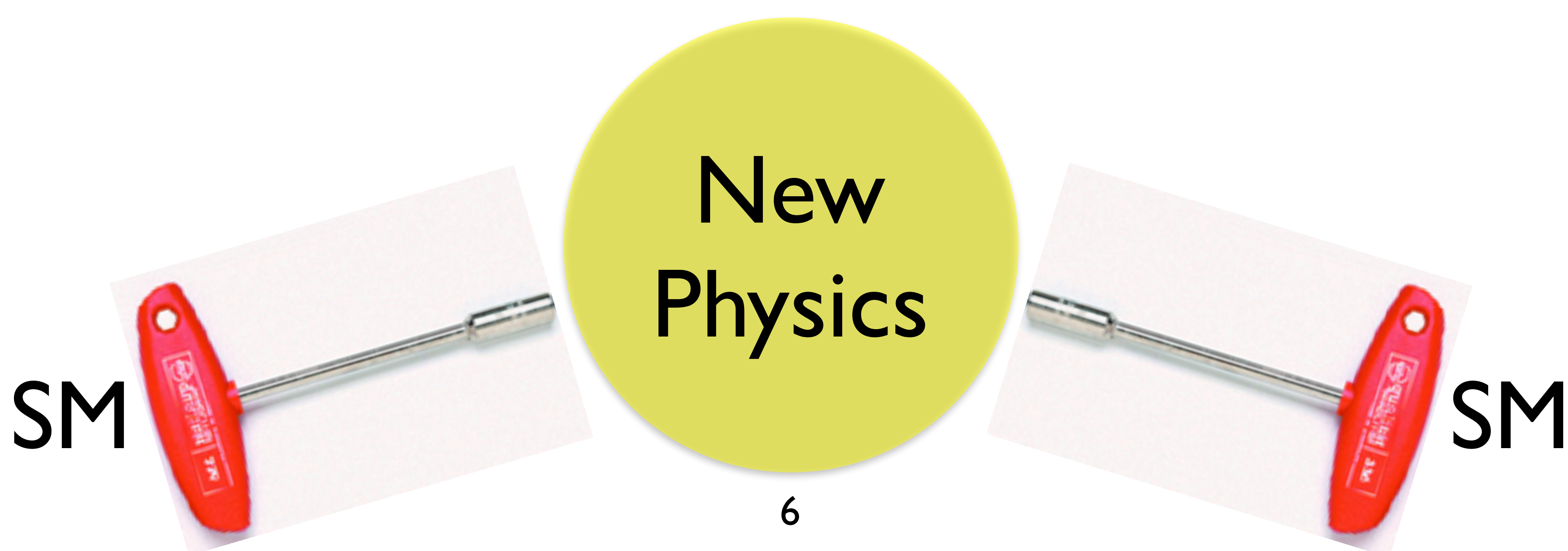
Neutrino physics is living the dream.

Exploring this new physics takes us outside of the HEP comfort zone. That's ok.

ν's compared to high energy colliders

ν		collider
neutrino models	⟷	BSM, SUSY, …
nucleon level & rad.corr.	⟷	pQCD, quarks, gluons
nuclear modeling	⟷	PDFs and hadrons

new physics probes require understanding the SM in an increasingly diverse range of processes



Physics	Tools

- *neutrino oscillations*
- *supernova constraints*
- *nucleon decay*
- *WIMP searches*
- *axion searches*
- *μ2e conversion*
- *EDMs*
- *0νββ*
- ...

lattice gauge theory

nuclear structure

perturbative, renormalizable QFT

astrophysics

atomic physics

geology

hydrodynamics

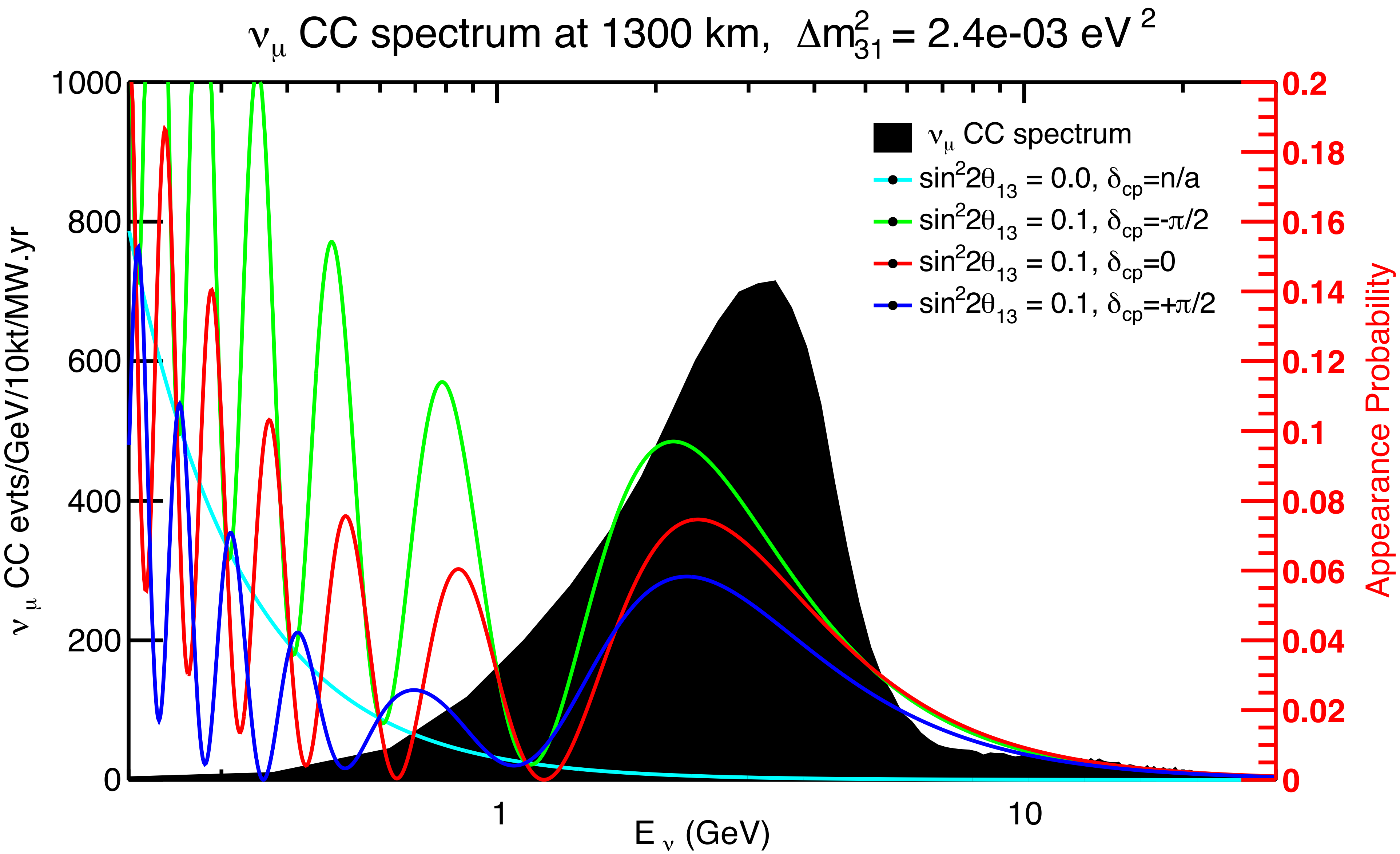
effective field theory

cosmology

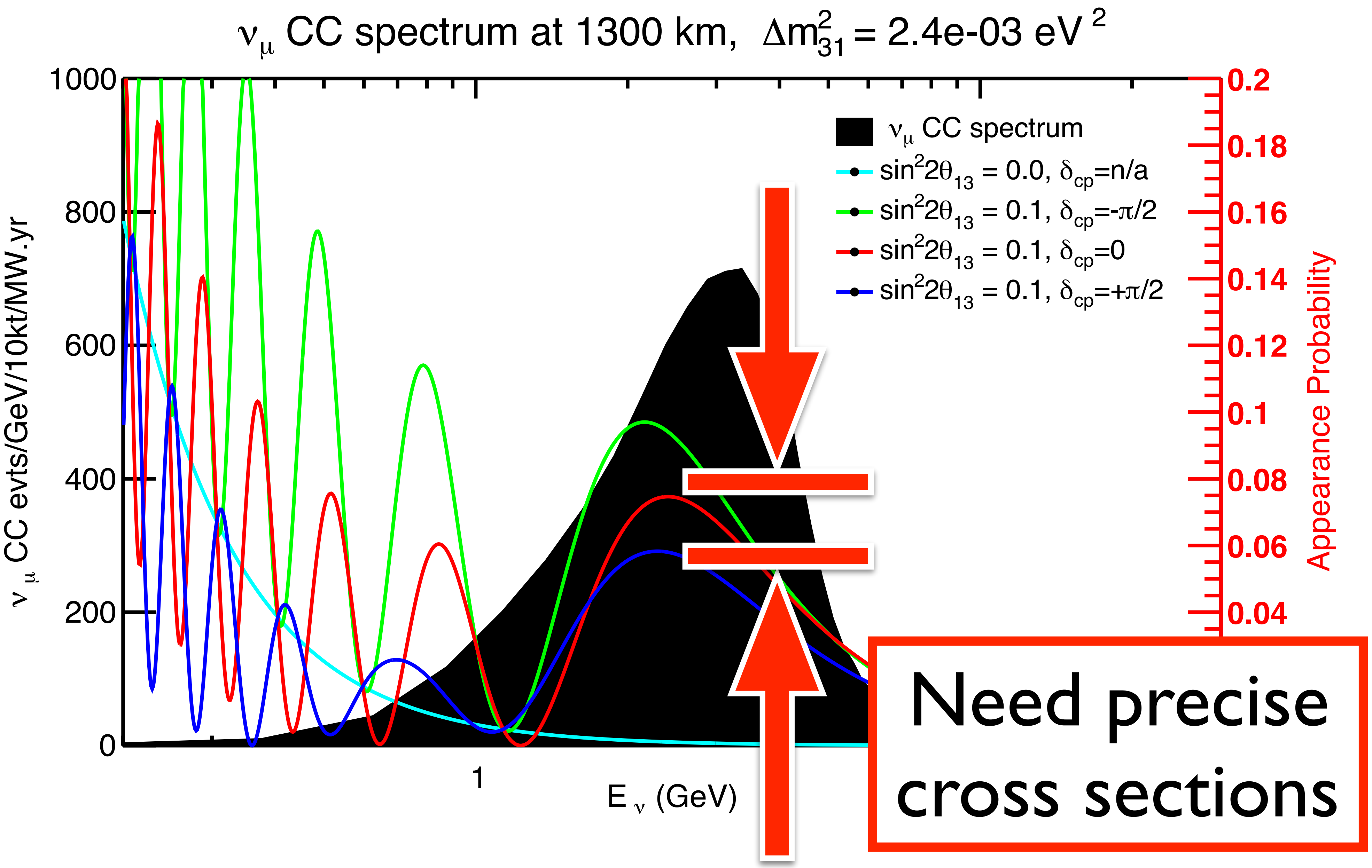
cosmic ray physics

...

a critical and exciting time, opportunities demanding adaption of existing tools and development of new tools



LBNE, 1307.7335
cf. Coloma, Huber et al., 1307.1243, 1311.4506;
Lalakulich and Mosel, 1311.7288



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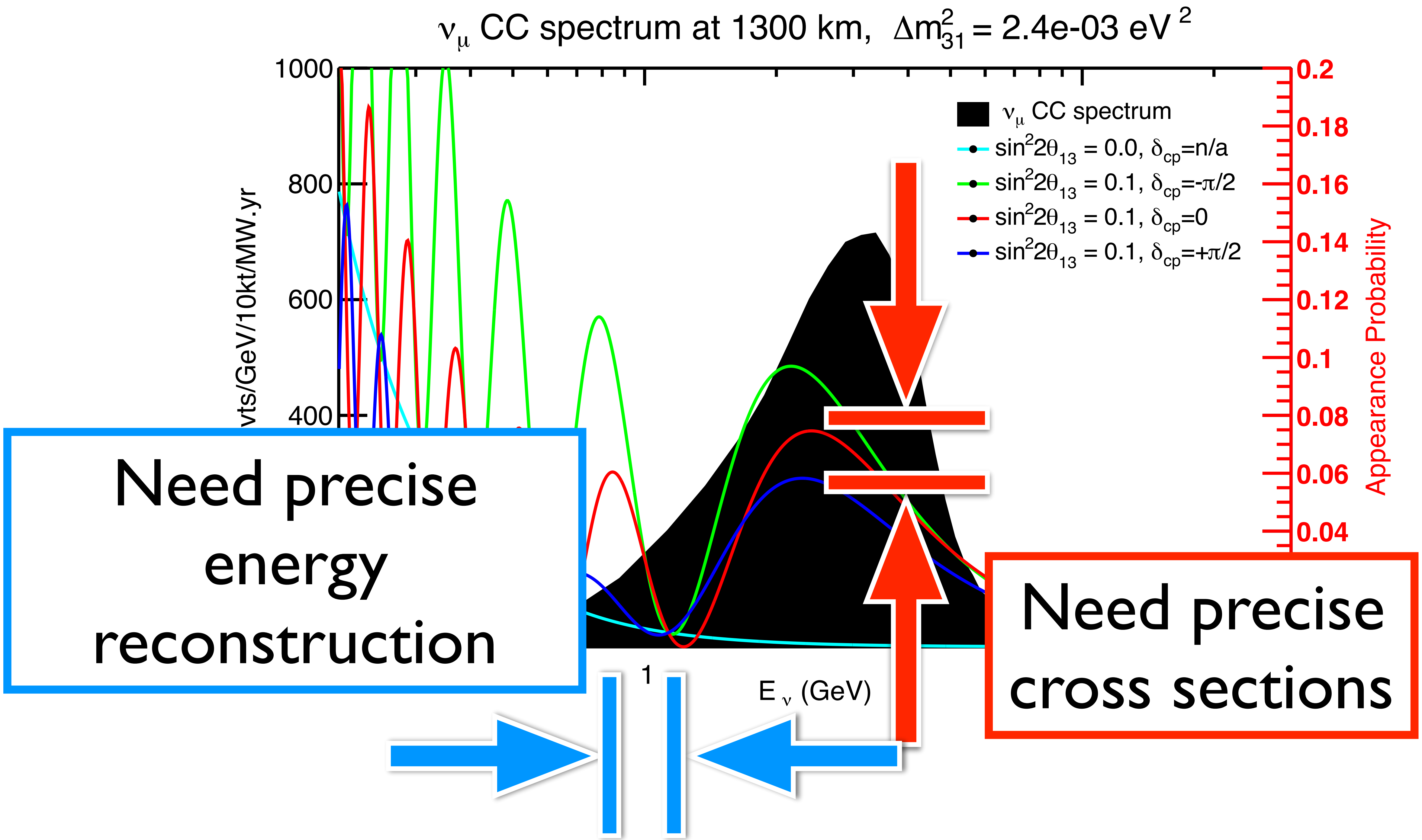

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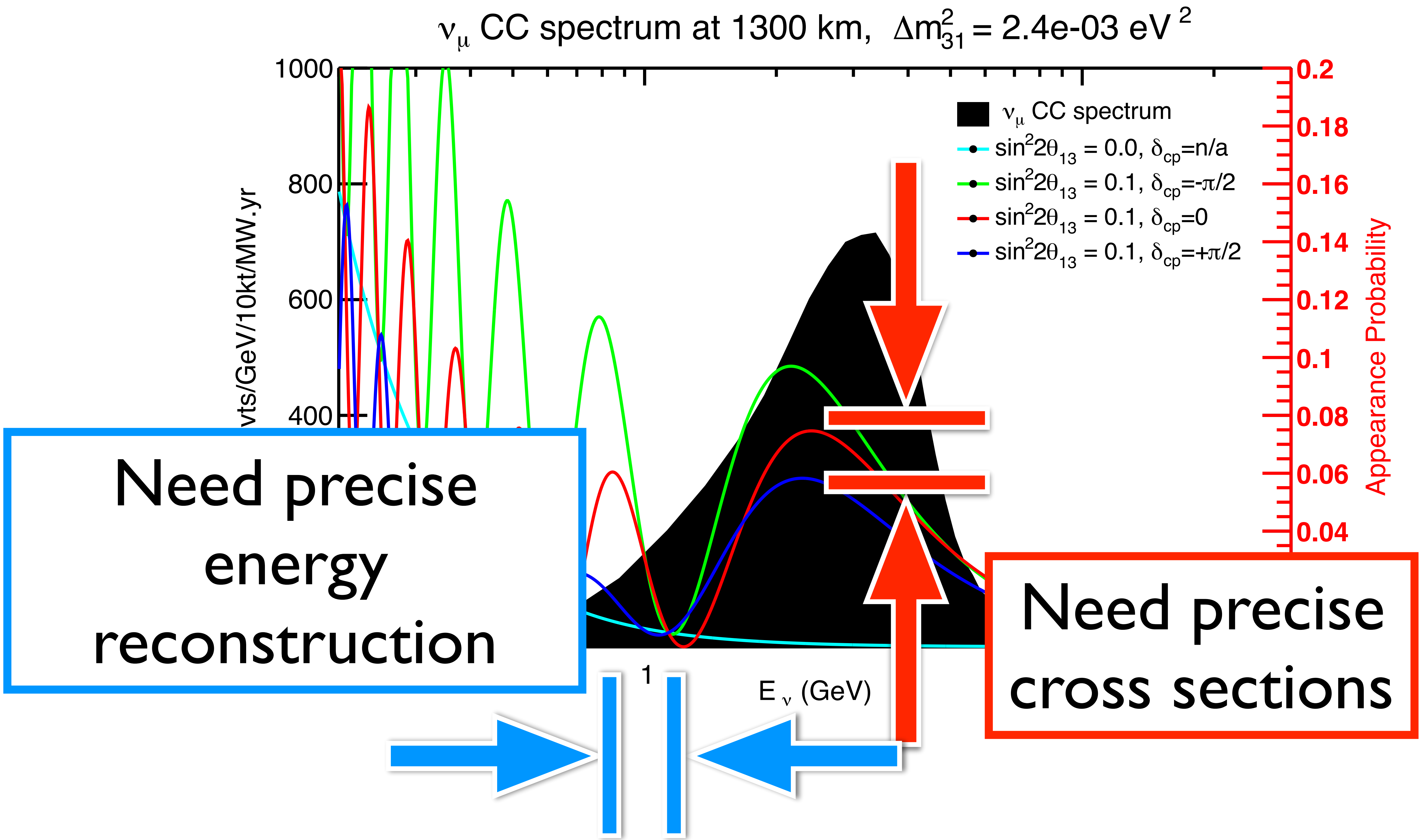

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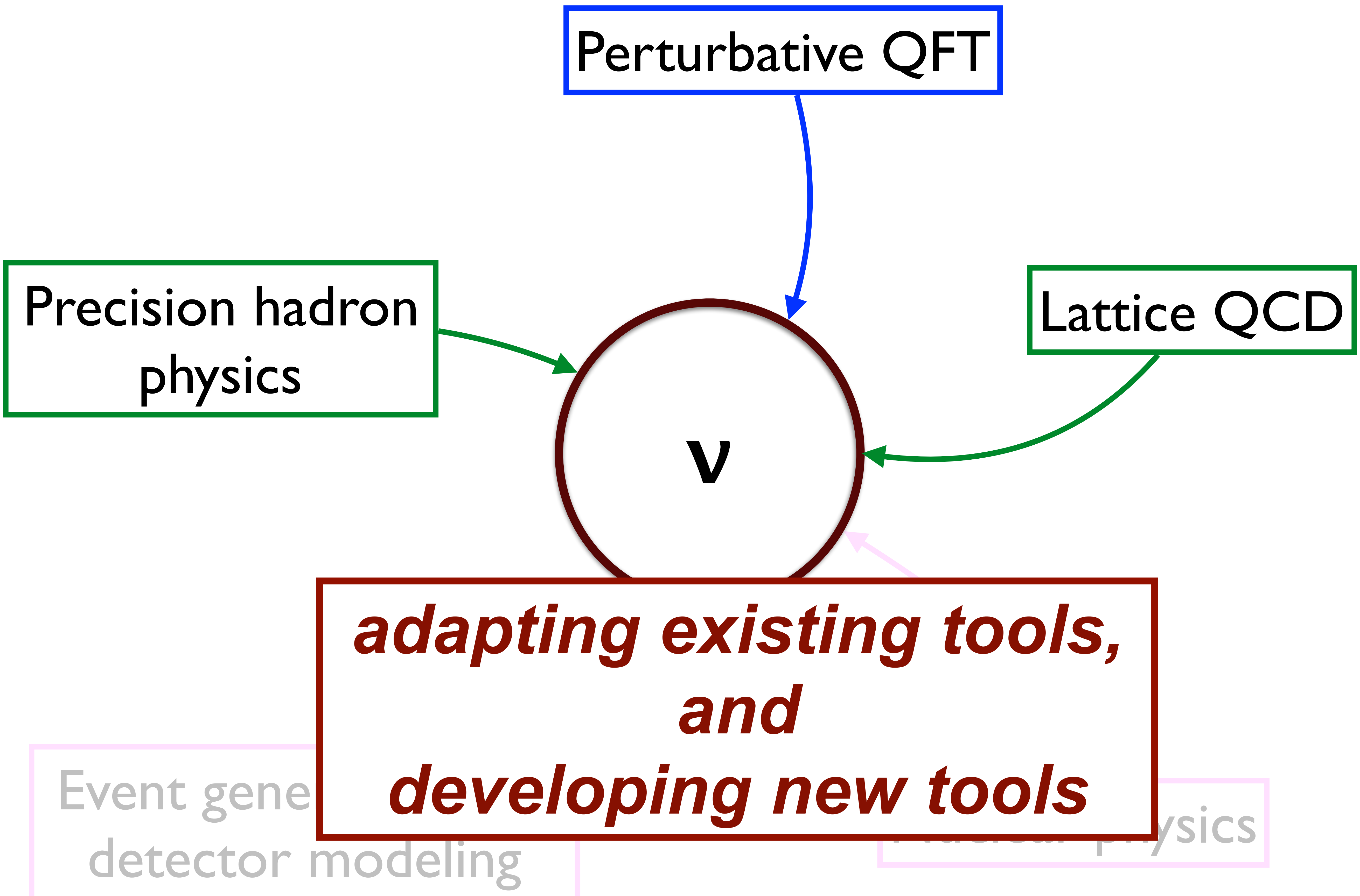
Many related activities and applications, over a wide energy range:

- **sterile neutrino searches**
- **reactor, supernova, astrophysical, solar, cosmological ν's**
- **proton decay, …**

Focus here on ~GeV ν cross sections for oscillation experiments

This is a challenging problem. HEP Theory is…



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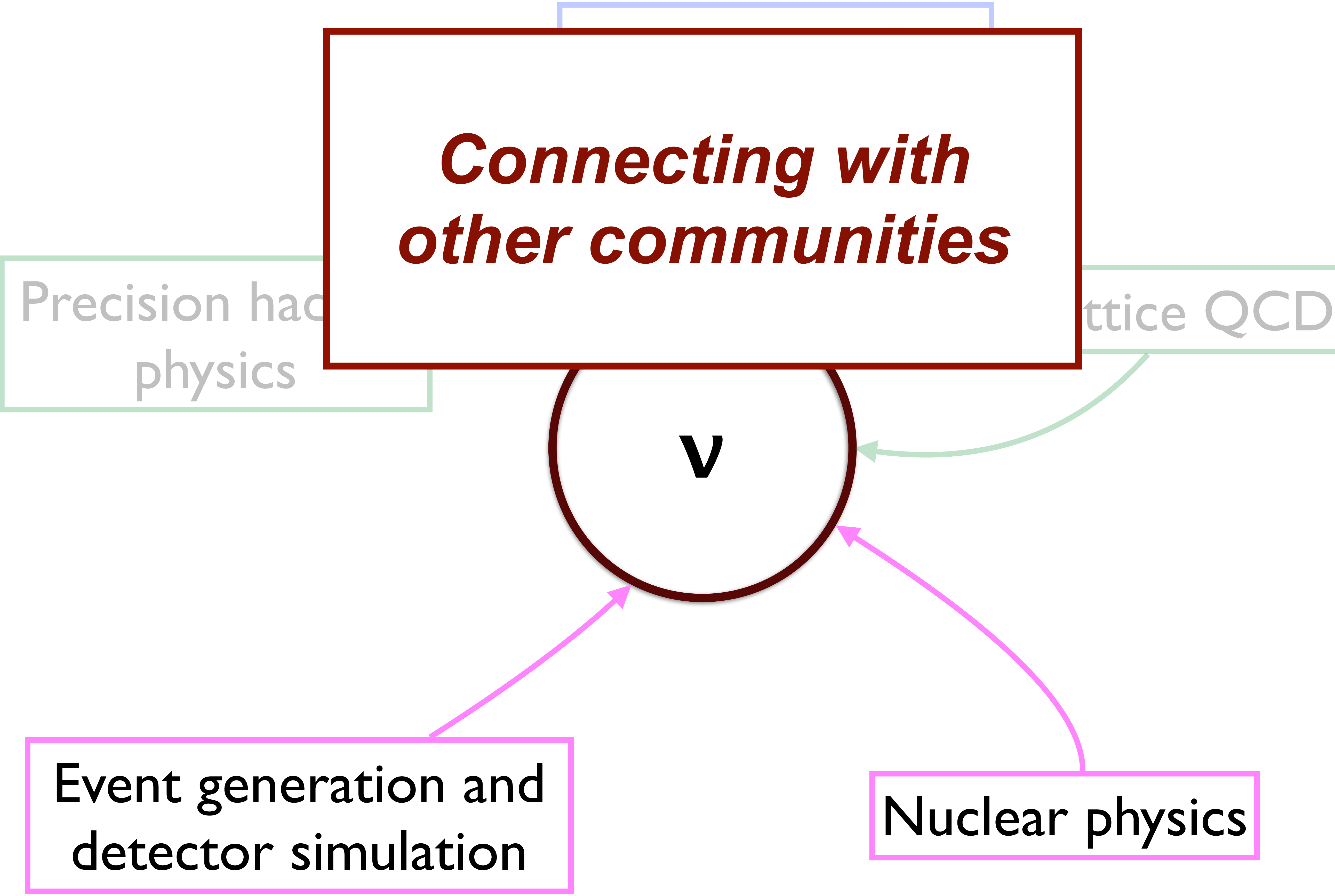


Consider some very basic properties of nucleons

- scattering by the basic WIMP
- scattering by electrons (or muons)
- scattering by neutrinos

Surprising, recent and important results in each case

Directly relevant to neutrino cross section program

Neutrino physics benefits from interplay with other fields

- the tools developed for neutrino cross sections have wide applicability

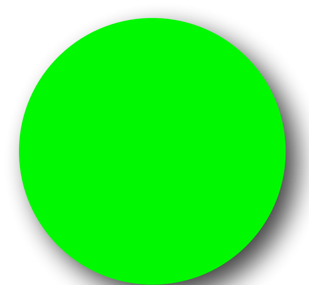
- application to other processes acts both as validation, and probes separately motivated fundamental physics

- QCD and nucleon/nuclear structure key to understanding neutrinos, DM, proton radius puzzle, …

- nuclear scattering by the basic WIMP

basic WIMP = electroweak triplet (color, hyper charge neutral)

- nuclear scattering by the basic WIMP



target nucleus

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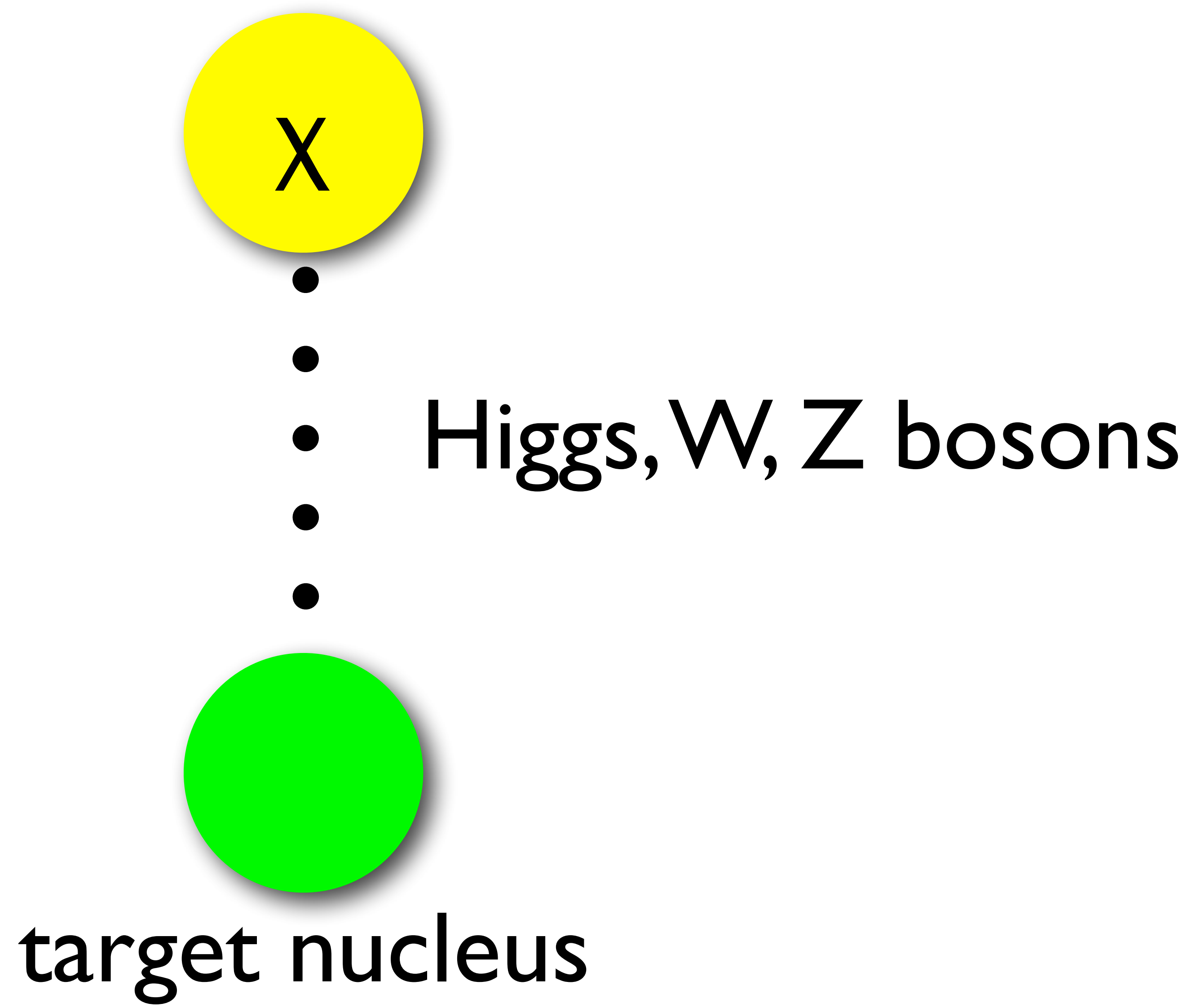

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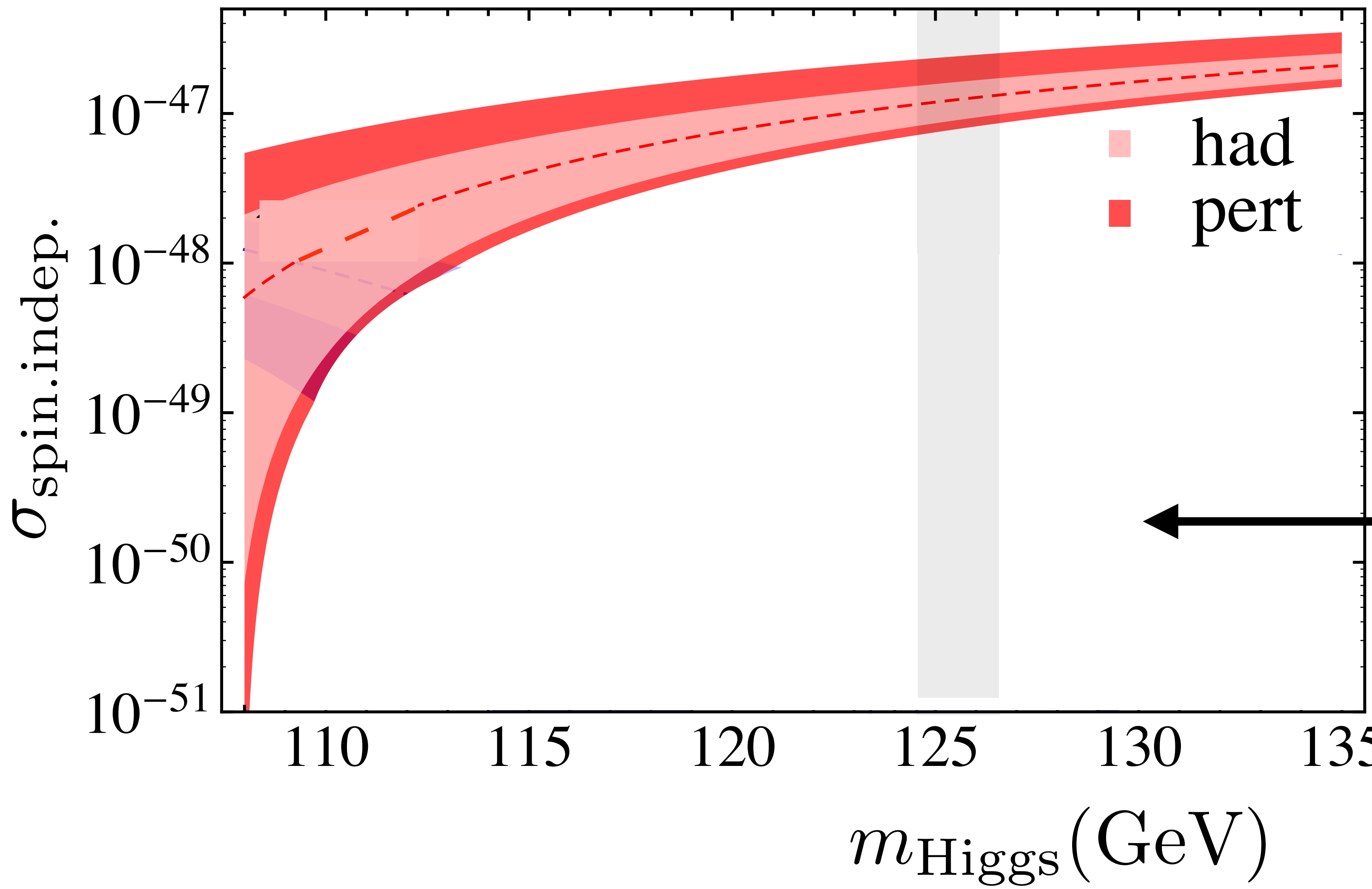
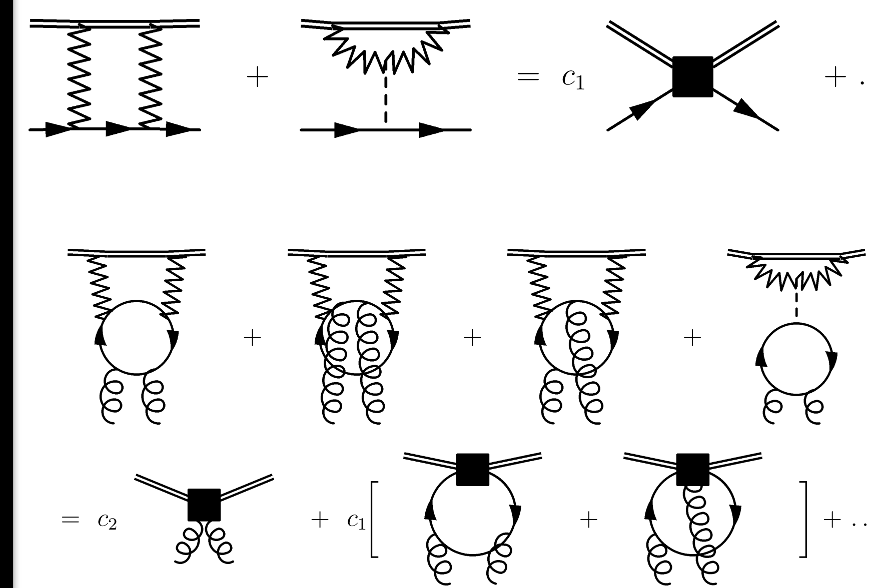
basic WIMP = electroweak triplet (color, hyper charge neutral)

Model independent prediction for heavy WIMP scattering

RJH, M.P. Solon (2014)

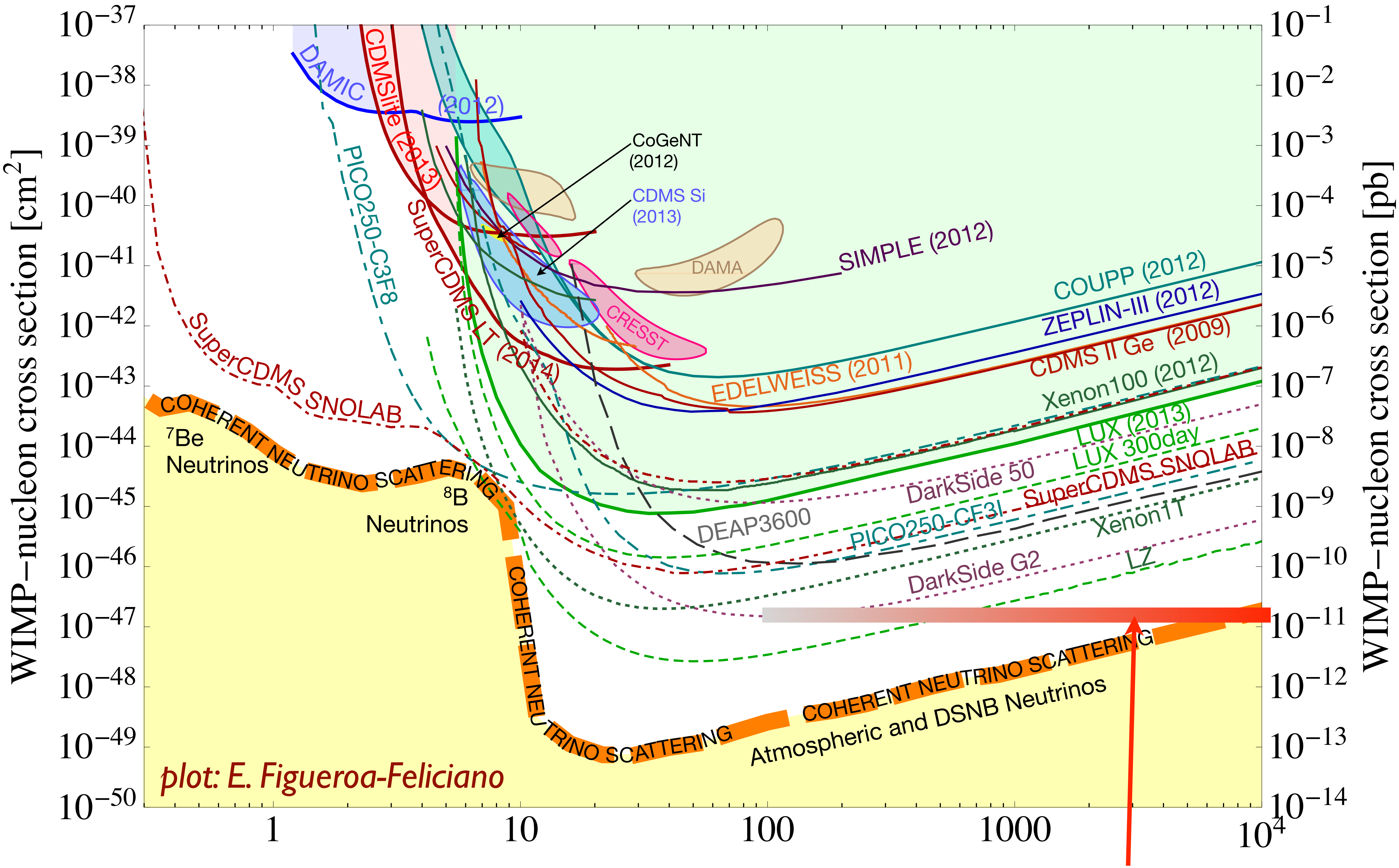


Heavy WIMP EFT



definite prediction of Standard model, but

- QCD uncertainty, both perturbative and nonperturbative

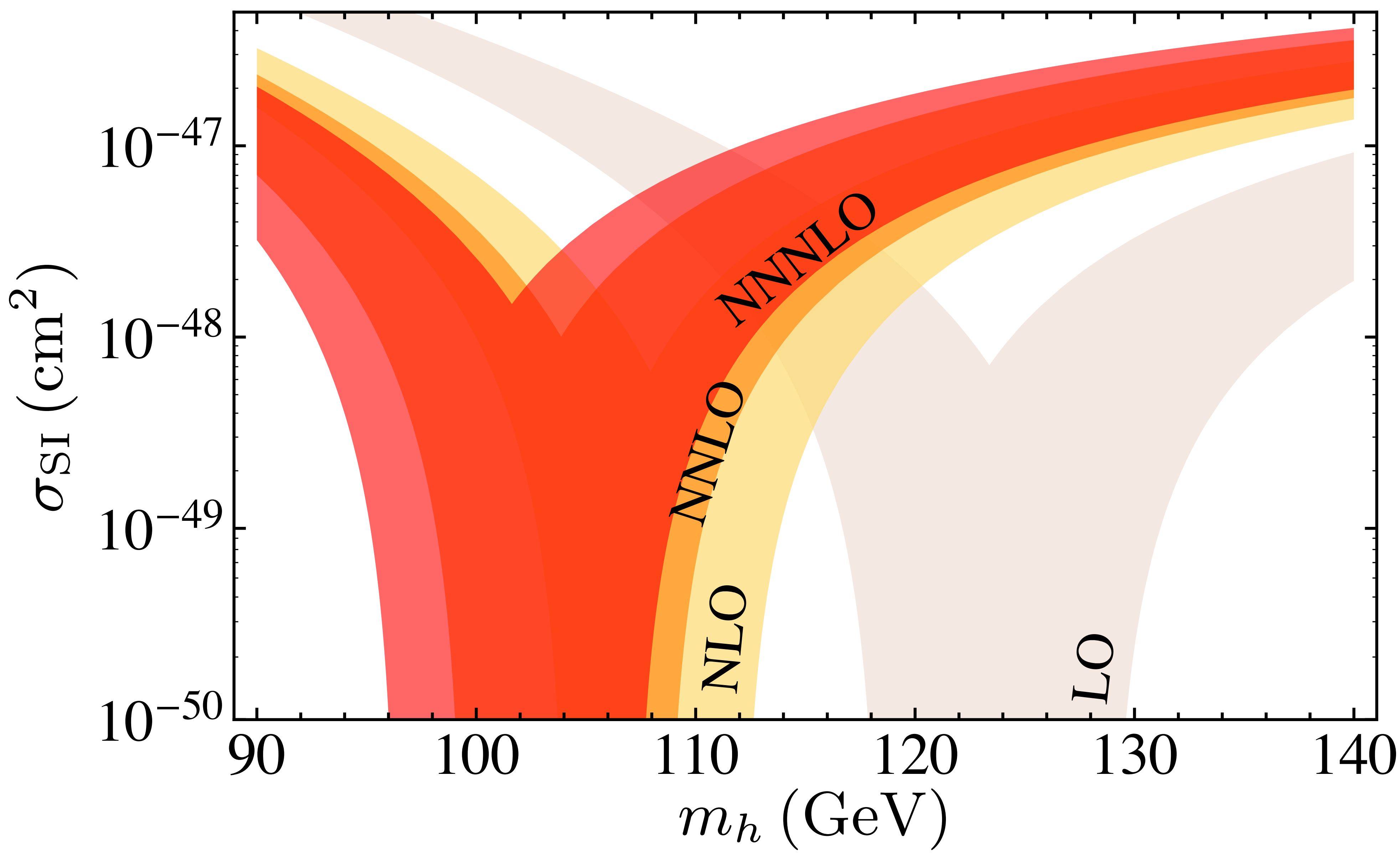


~ thermal relic

Strong motivation for pushing to neutrino floor at ~TeV mass

QCD aspects of WIMP-nucleus scattering

perturbative QCD is important:



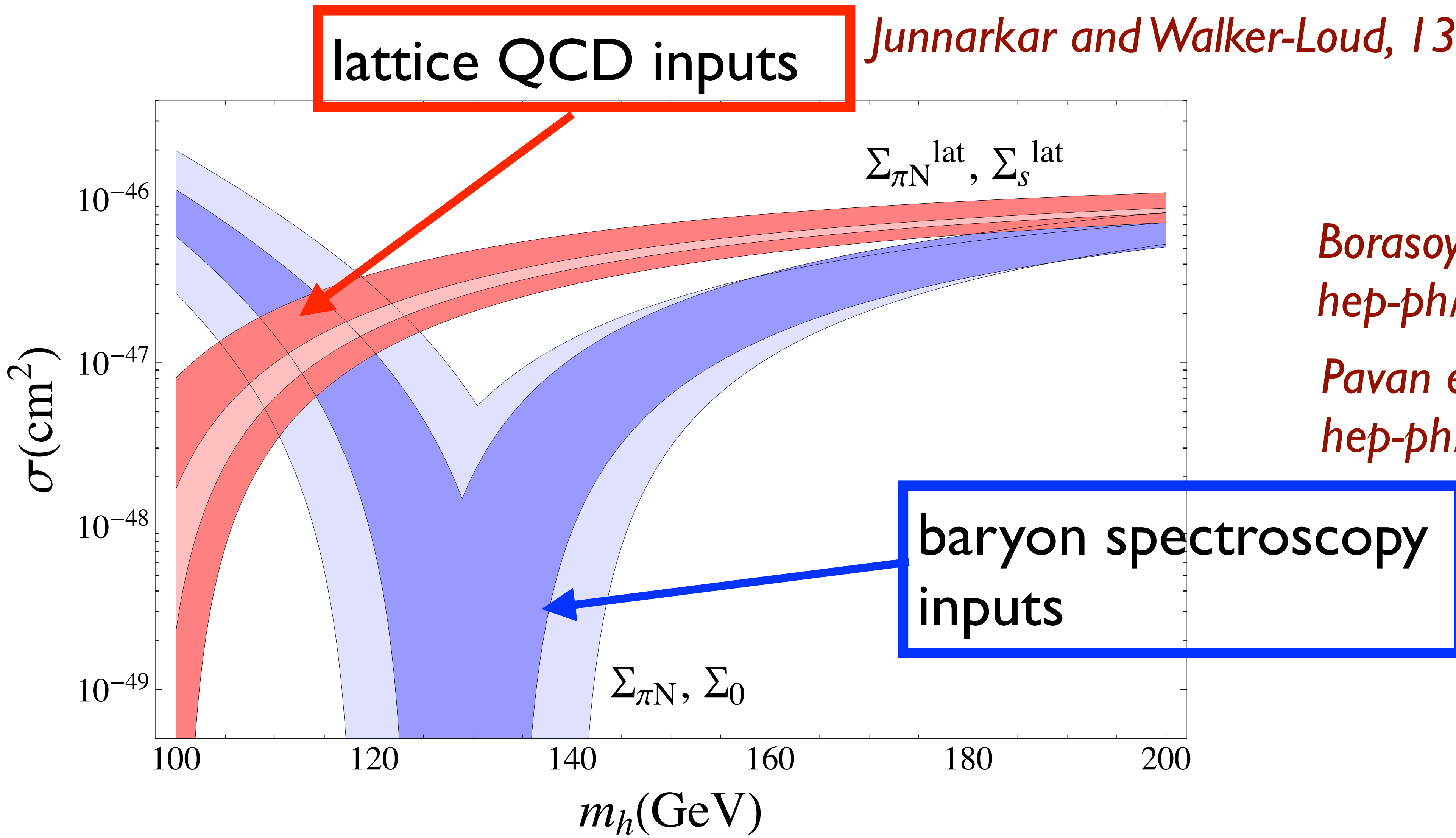
NLO corrections essential for correct order of magnitude

QCD aspects of WIMP-nucleus scattering

nucleon-level amplitudes are important (important impact from lattice QCD)

Durr et al. 1109.4265

Junnarkar and Walker-Loud, 1301.1114



Borasoy and Meissner, hep-ph/9607432

Pavan et al. hep-ph/0111066

nuclear effects may also play a role (amplitude cancellation at one-nucleon level)

QCD aspects of WIMP-nucleus scattering

lessons for neutrino cross sections

- important interplay of perturbative QFT, nucleon-level amplitudes and nuclear effects

- important inputs from lattice QCD

- all parts relevant for determining observability of WIMPs, and interpretation of next generation experiments

- elastic electron-proton scattering

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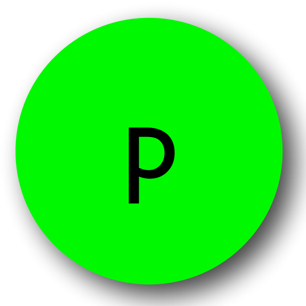

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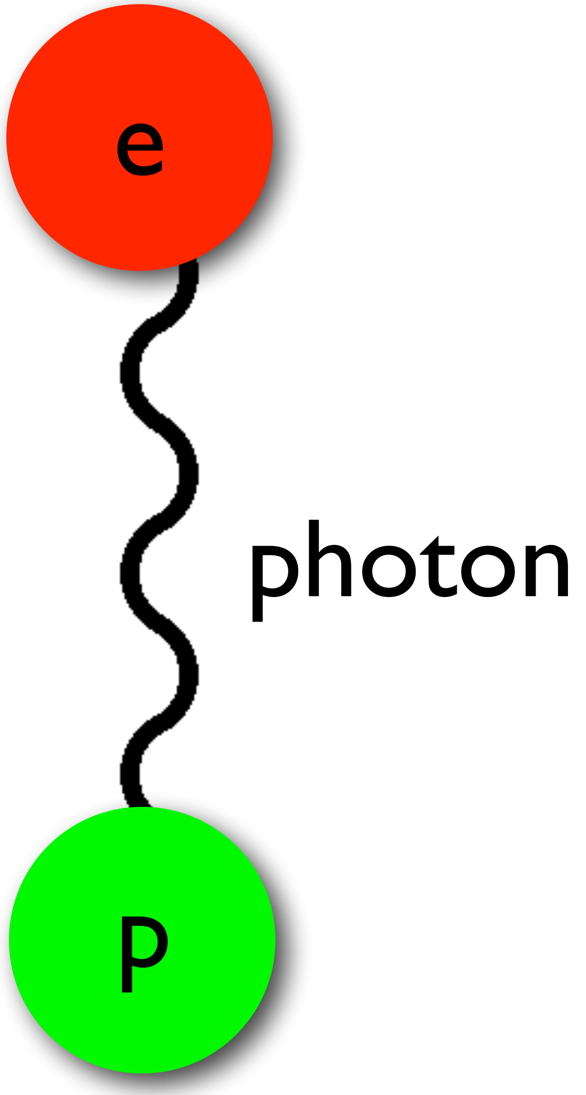
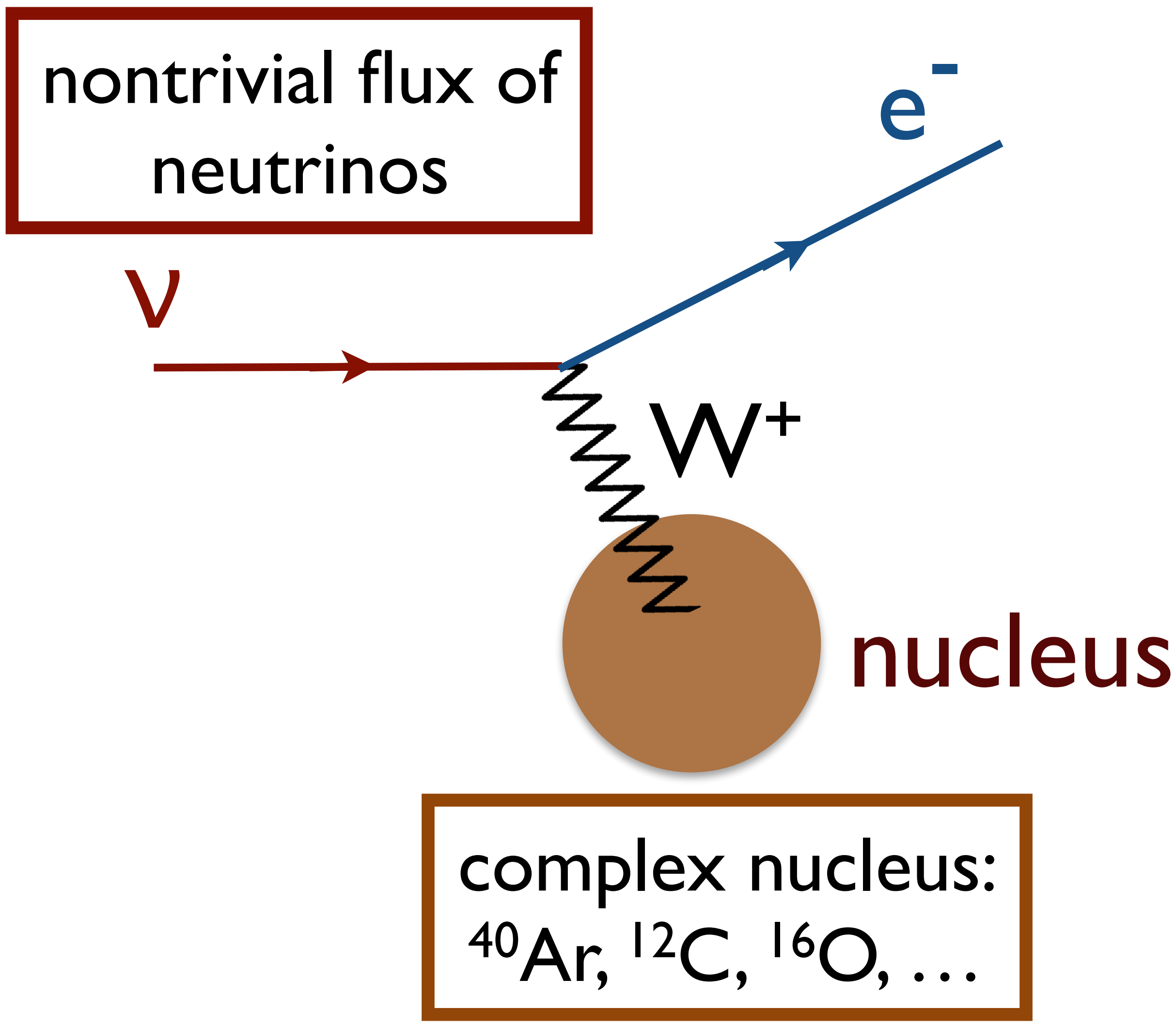
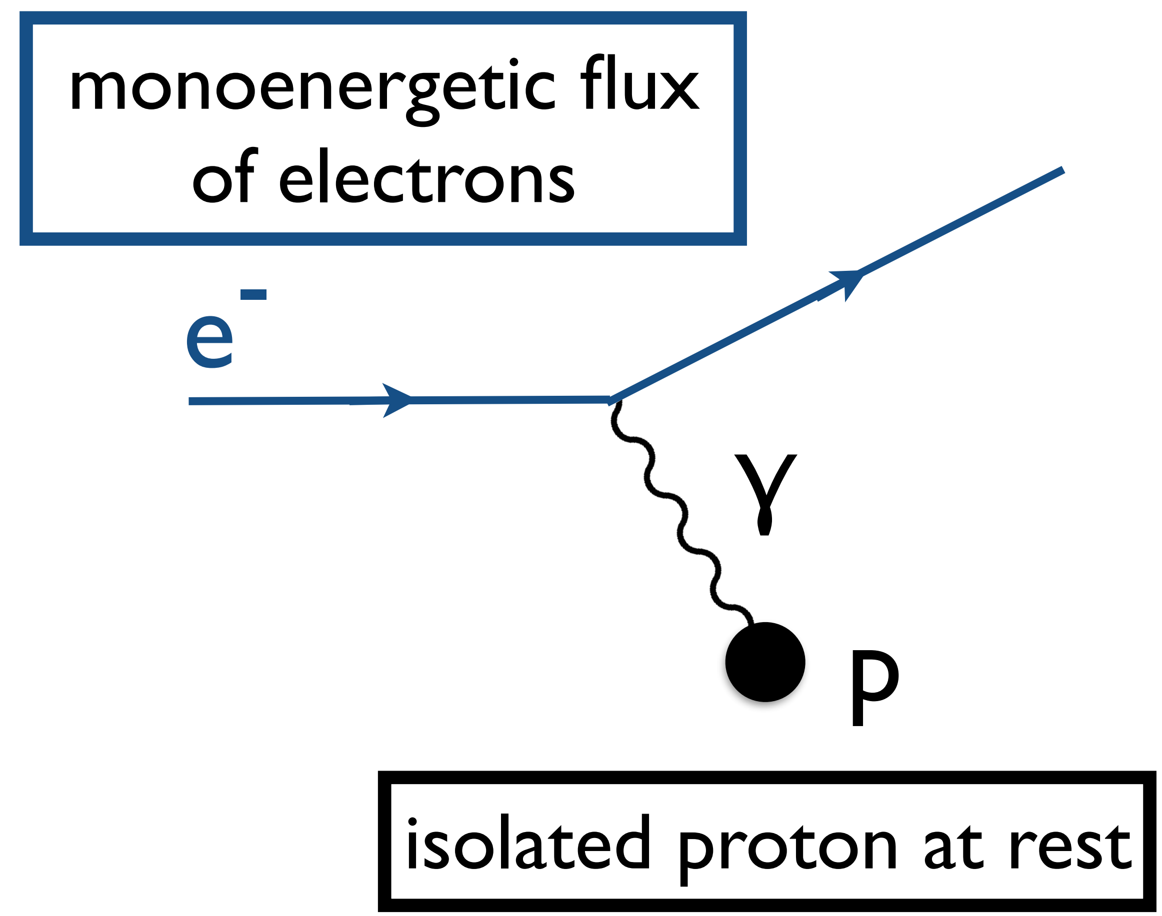


- elastic electron-proton scattering

- inputs to neutrino cross sections (vector form factors)
- a proving ground for both theory and experiment





Do we understand this problem with controllable uncertainties?

Some facts about the Rydberg constant puzzle (a.k.a. proton radius puzzle)

1) It has generated a lot of attention and controversy

2) The *most mundane* resolution necessitates:

- 5σ shift in fundamental Rydberg constant
- discarding or revising decades of results in e-p scattering and hydrogen spectroscopy

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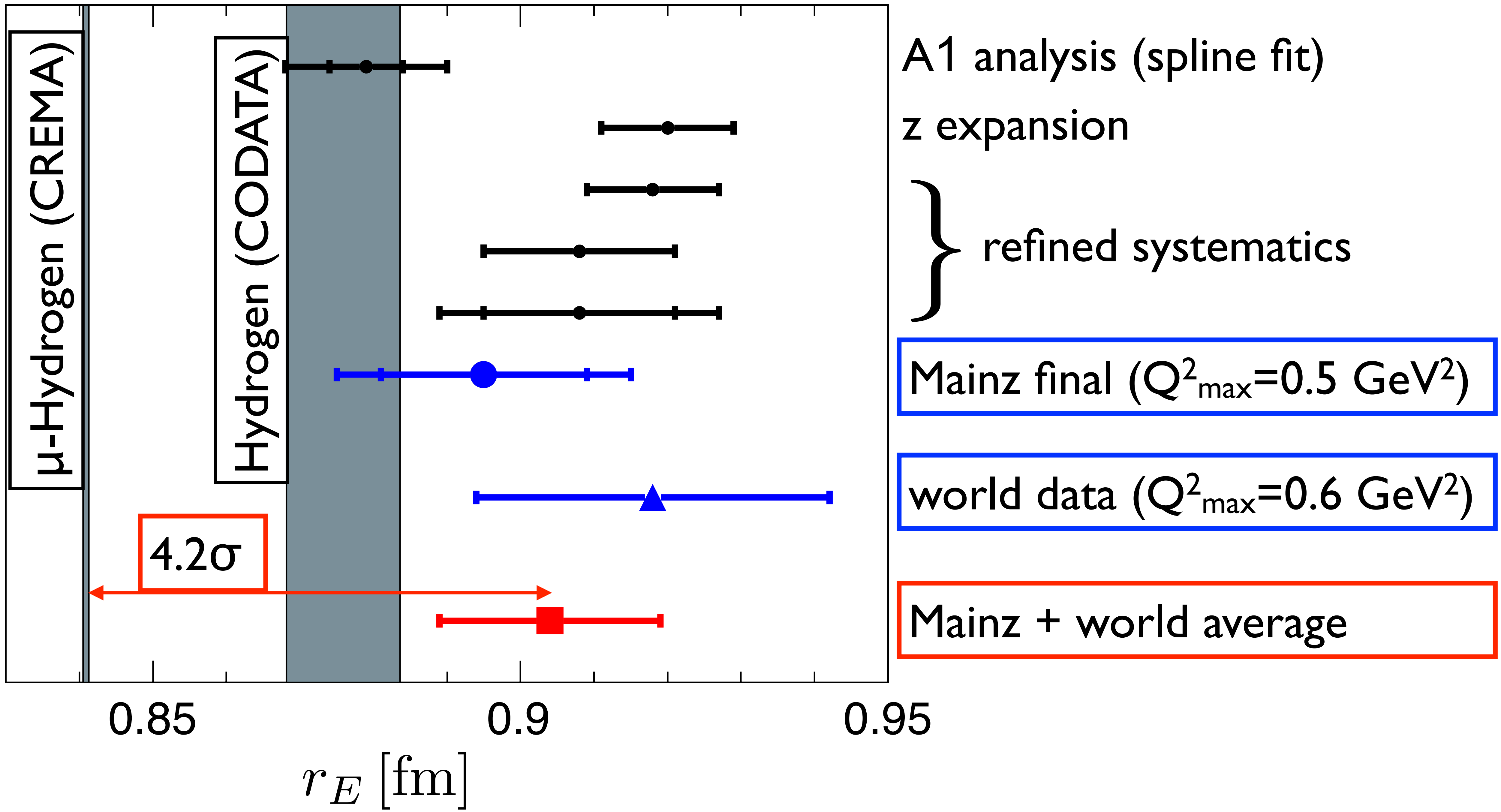
This *is* HEP's problem:

"The good news is that it's not my problem"

3) Systematic effects in electron-proton scattering impact neutrino-nucleus scattering, *at a level large compared to DUNE precision requirements*

experimental landscape: electron-proton scattering

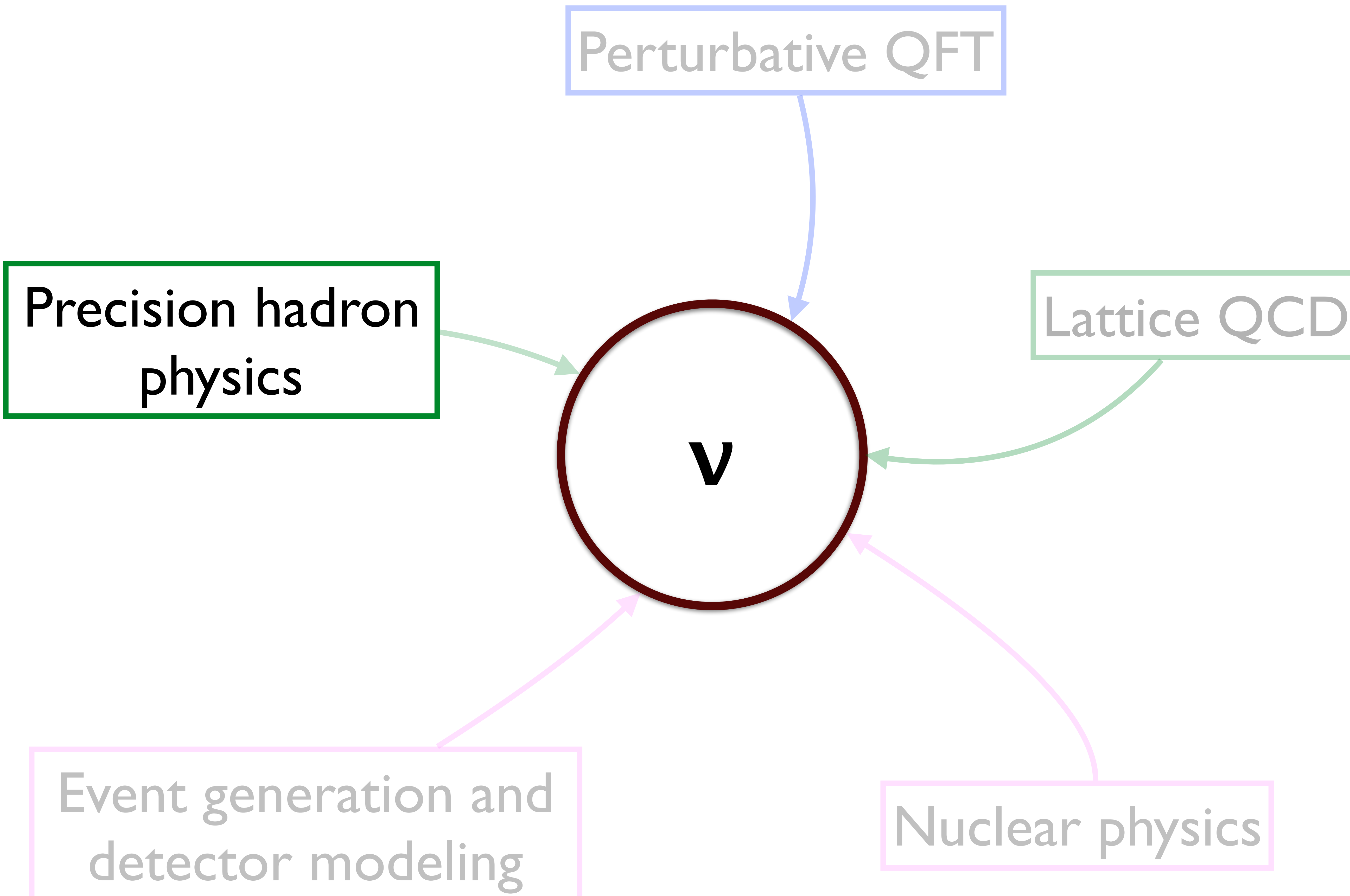
G. Lee, J. Arrington, RJH, 2015



r_E^{Mainz} = 0.895(14)(14) fm

r_E^{world} = 0.918(24) fm

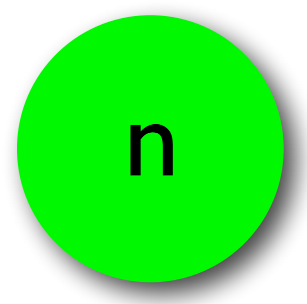
simple average: $r_E^{avg.}$ = 0.904(15) fm


Perturbative QFT
Precision hadron physics
Lattice QCD
ν
Event generation and detector modeling
Nuclear physics

- nucleon scattering by the neutrino

First step in a program for error bars on neutrino-nucleus cross sections: the most elementary process.

- nucleon scattering by the neutrino



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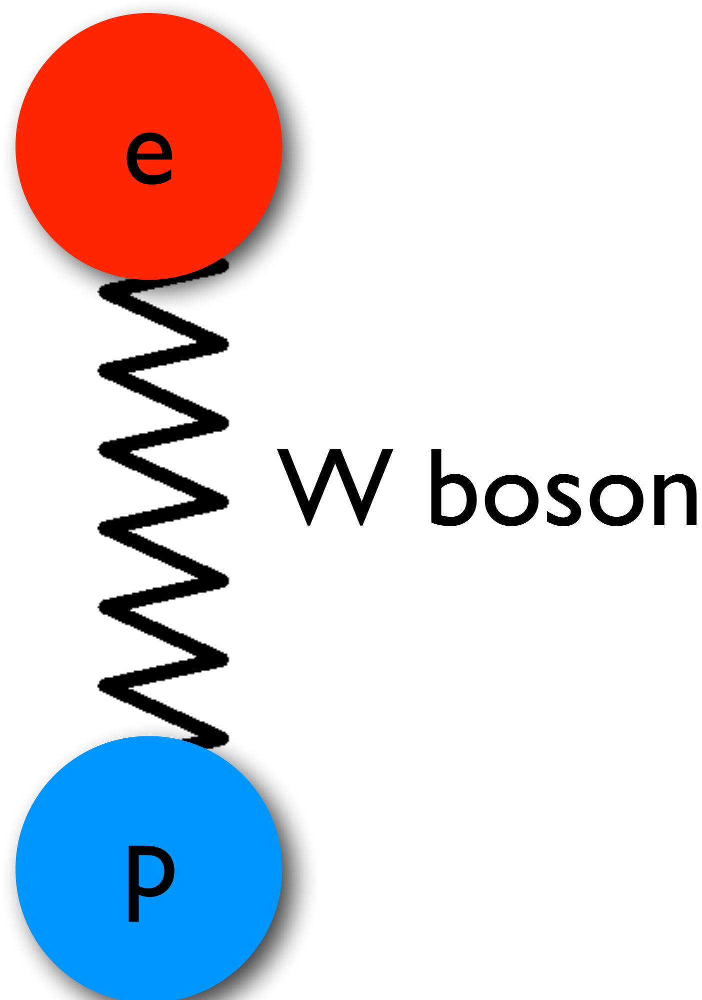

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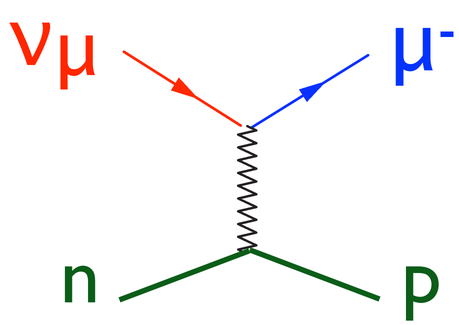
First step in a program for error bars on neutrino-nucleus cross sections: the most elementary process.

Start with the basic process



$$\sigma(\nu n \to \mu p) = |\cdots F_A(q^2) \cdots|^2$$

poorly known axial-vector form factor

What is the status of nucleon-level amplitudes, the basic building block for neutrino-nucleus cross sections?

A common ansatz for F_A has been employed for the last ~40 years:

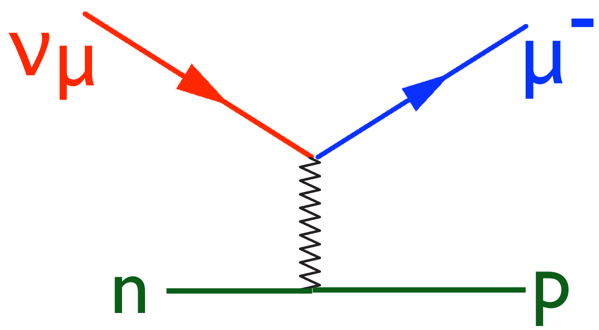
$$F_A^{\text{dipole}}(q^2) = F_A(0)\left(1 - \frac{q^2}{m_A^2}\right)^{-2}$$

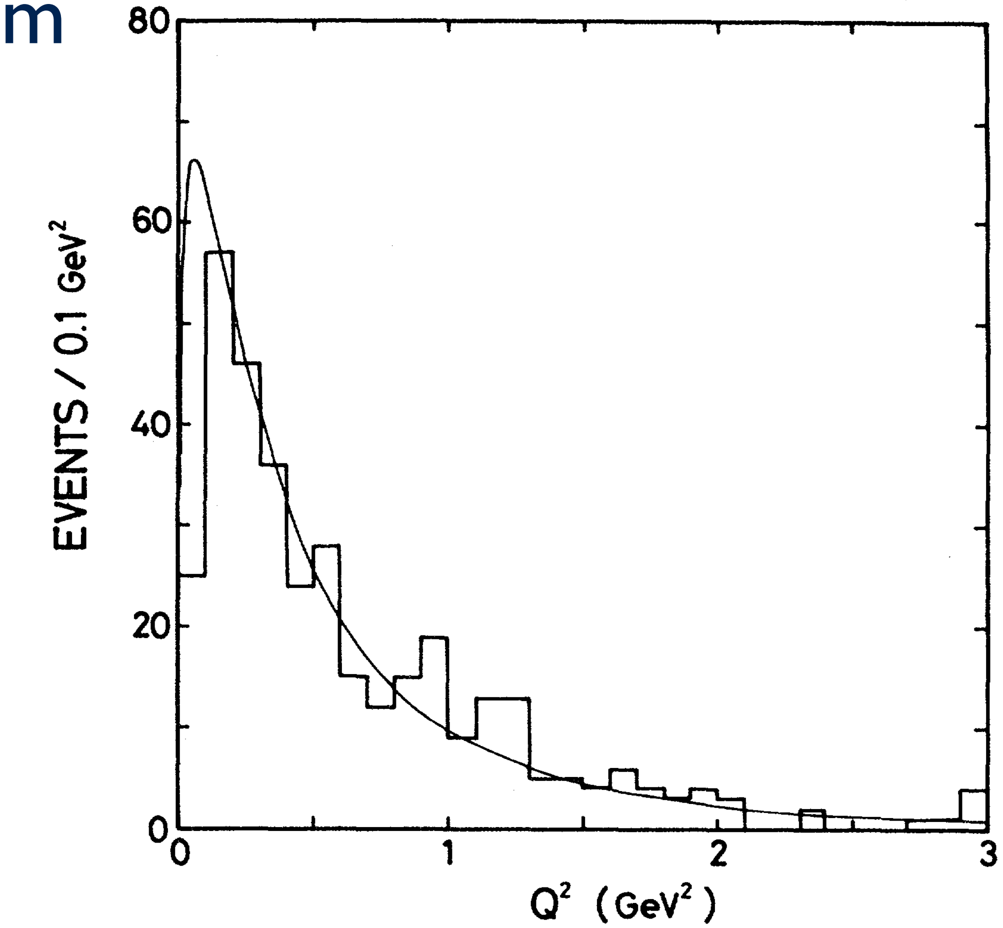
Inconsistent with QCD.

Typically quoted uncertainties are small (e.g. compared to proton charge form factor)

$$\frac{1}{F_A(0)} \frac{dF_A}{dq^2}\bigg|_{q^2=0} \equiv \frac{1}{6} r_A^2 \qquad r_A = 0.674(9)\,\text{fm}$$

Best source of almost-free neutrons: deuterium





Fermilab 15-foot deuterium bubble chamber, PRD 28, 436 (1983)

Deuterium bubble chamber data

- small(-ish) nuclear effects
- small(-ish) experimental uncertainties
- small statistics, ~3000 events in world data

also:

ANL 12-foot deuterium bubble chamber, PRD 26, 537 (1982)

BNL 7-foot deuterium bubble chamber, PRD23, 2499 (1981)

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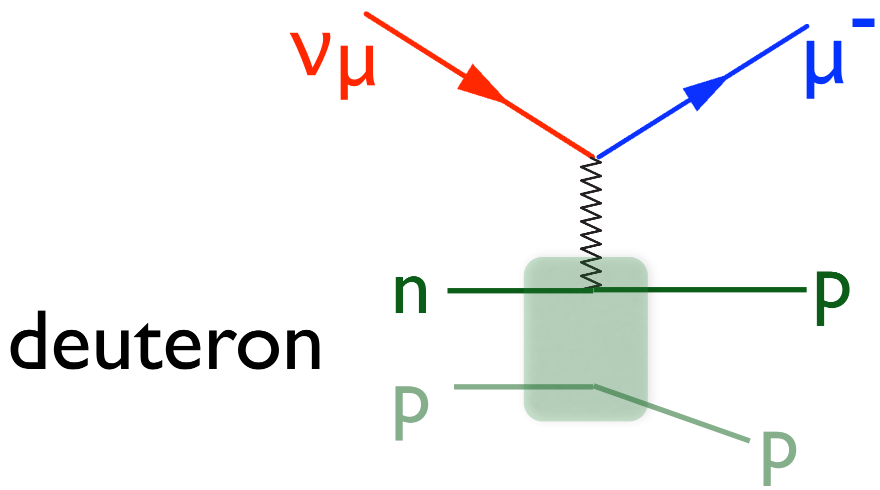

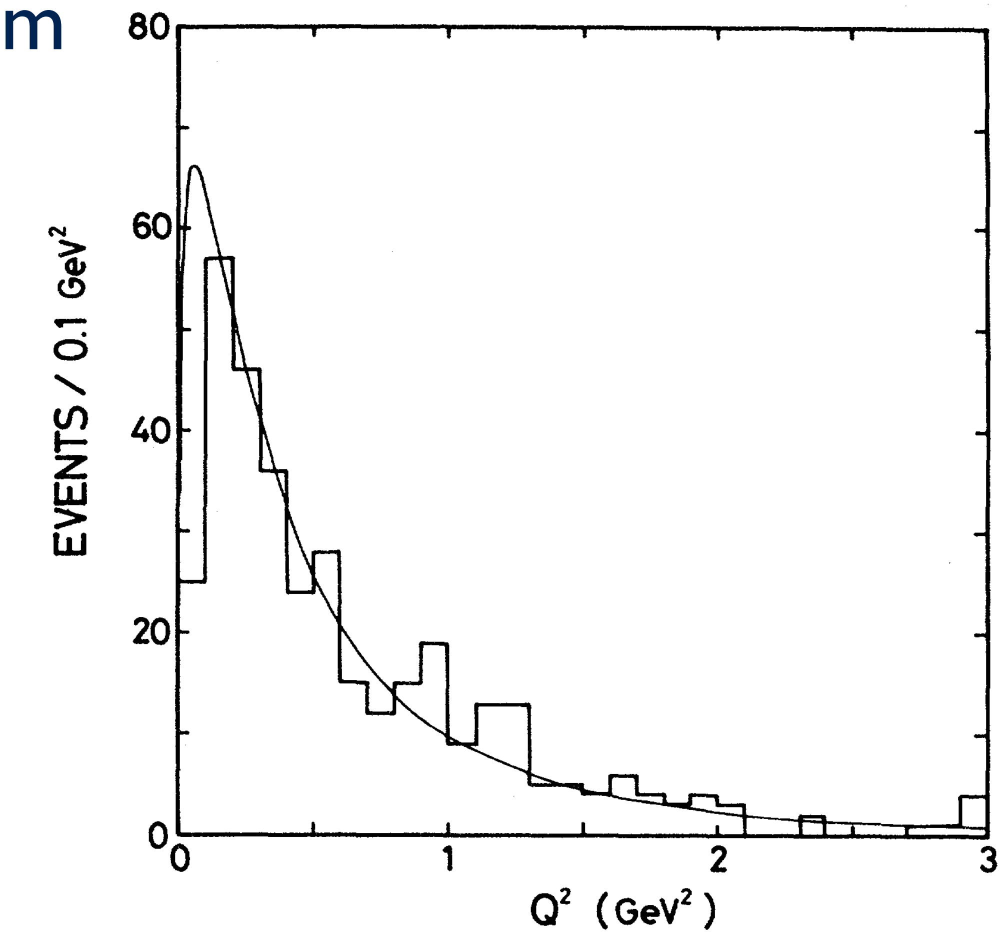

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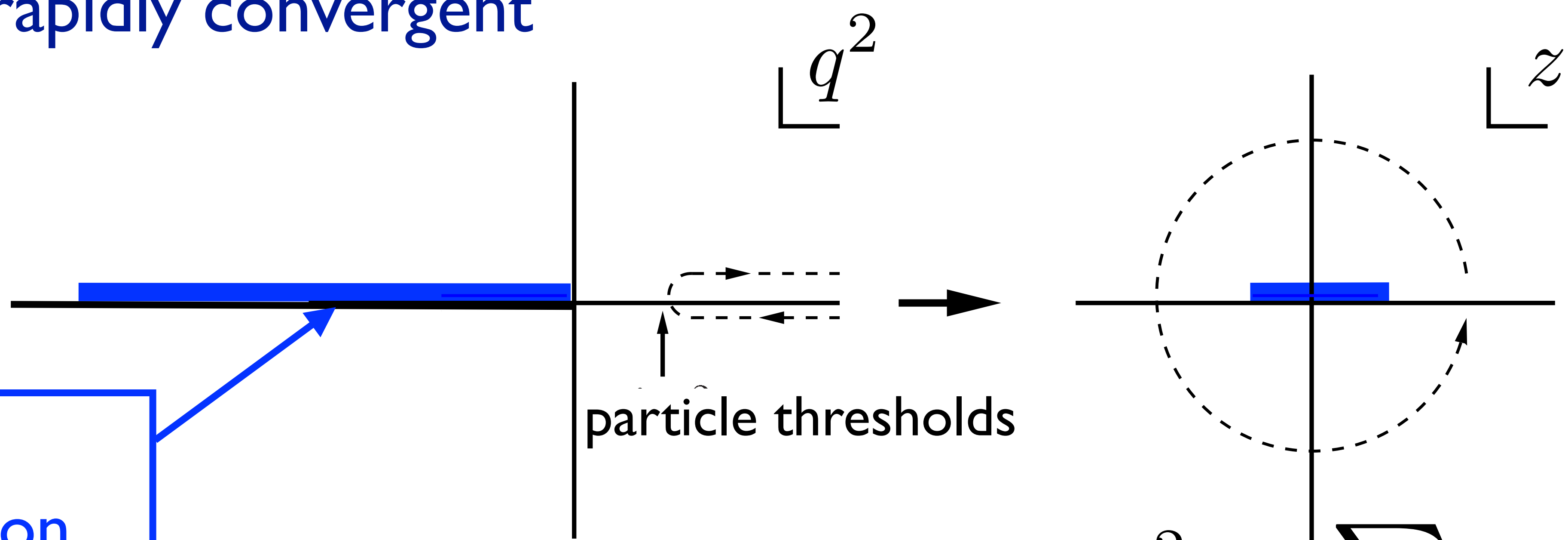
HEP toolbox is being applied to precision lepton-nucleon scattering

- Basic problem: don't know form factor shapes, so don't know what we're constraining
- Underlying QCD tells us that Taylor expansion in appropriate variable is rapidly convergent



experimental kinematic region

$$F(q^2) = \sum_k a_k [z(q^2)]^k$$

coefficients in rapidly convergent expansion encode nonperturbative QCD

Systematically improvable, quantifiable uncertainties

This approach has been very successful in other processes

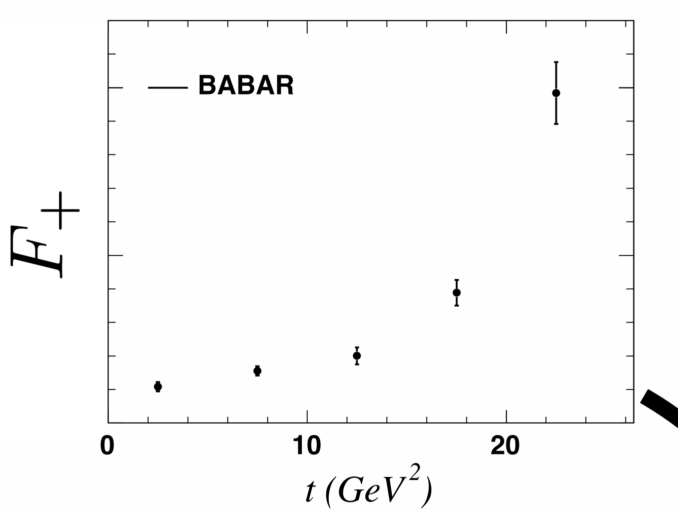
E.g., $B \to \pi e \nu$: $|z|<0.28$

(Similarly $K \to \pi e \nu$: $|z|<0.047$)

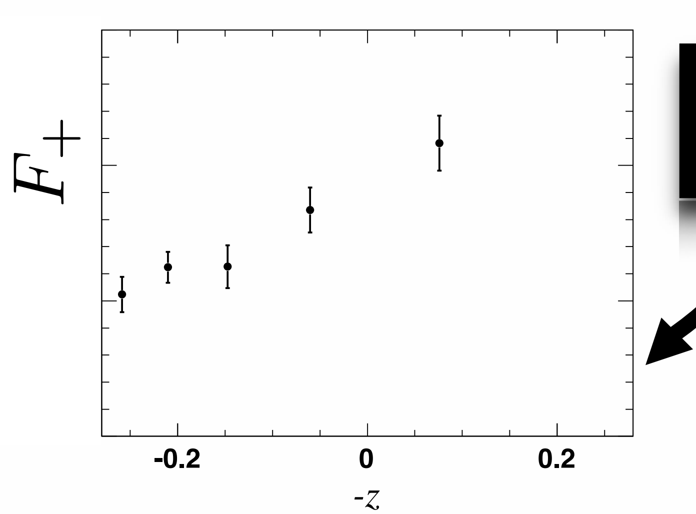
RJH hep-ph/0607108, KTeV hep-ex/0608058

$$\frac{d\mathcal{B}}{dq^2} \sim |V_{ub}|^2 |F_+(q^2)|^2$$

Becher, RJH hep-ph/0509090



simple shape in z



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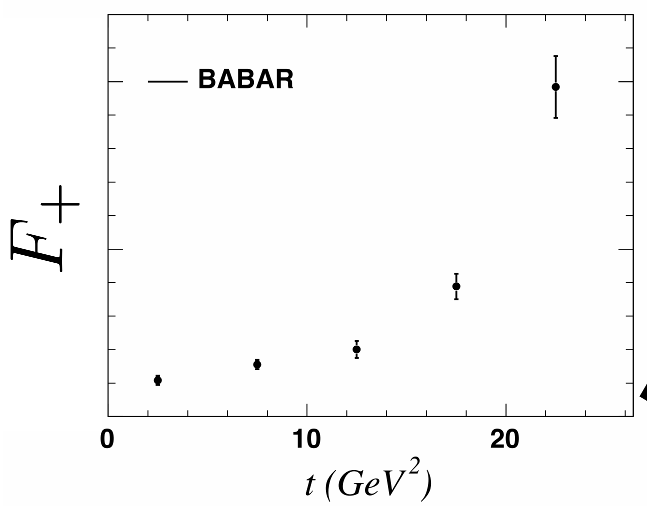
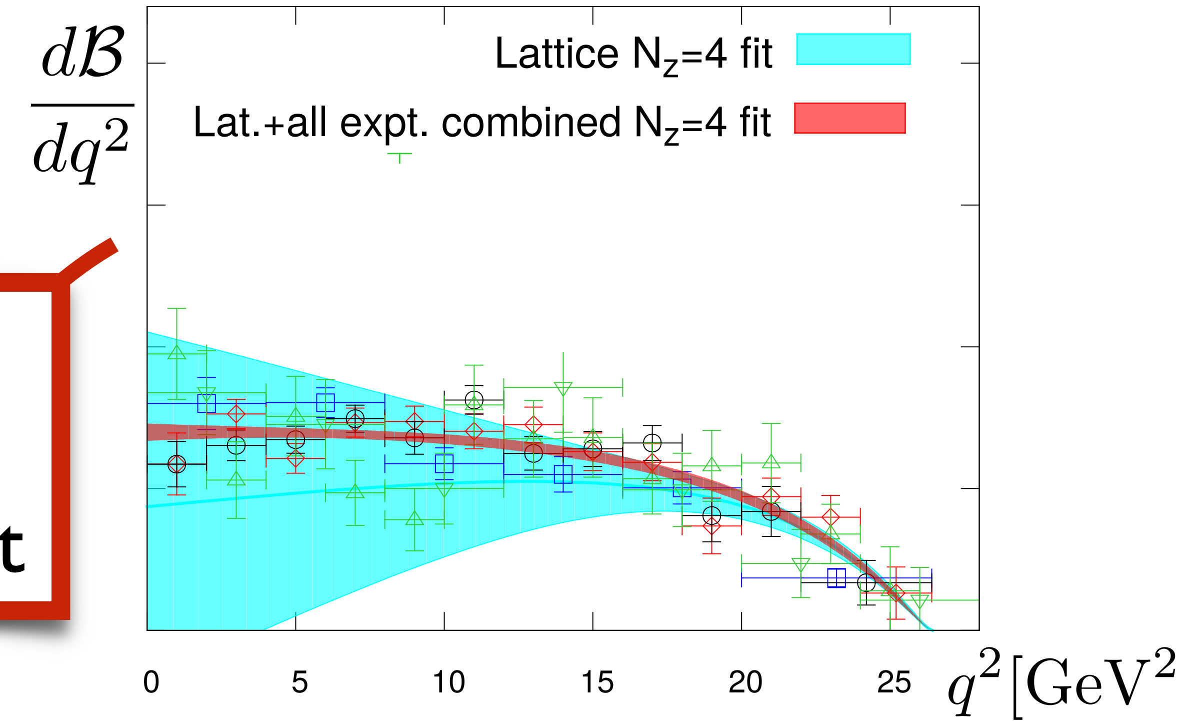
RJH hep-ph/0607108, KTeV hep-ex/0608058

Fermilab lattice/MILC 1503.07839

Becher, RJH hep-ph/0509090

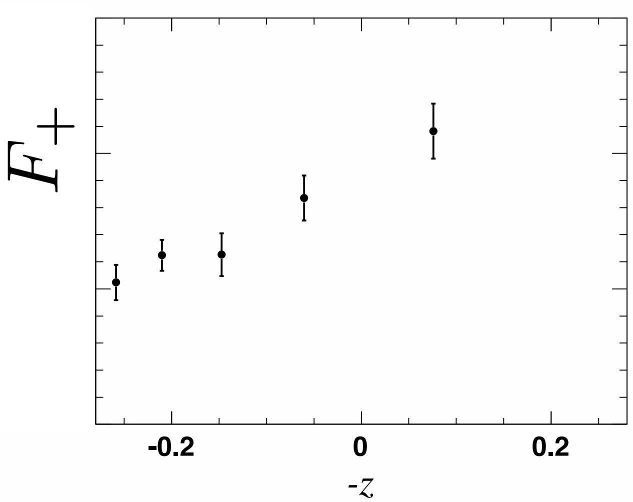


systematic combination of lattice, experiment

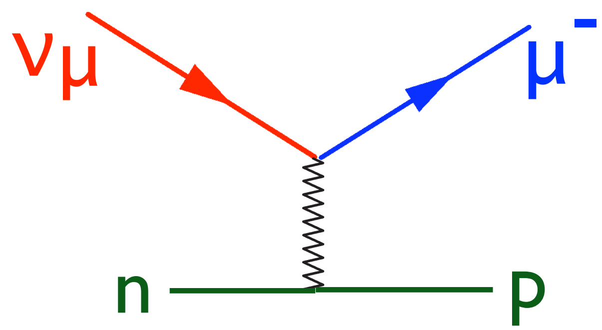


simple shape in z

world's best determination of $|V_{ub}|$



Adapt these tools for neutrino - hadron scattering



$\nu_\mu + n \rightarrow \mu^- + p$,
$0 < Q^2 < 3$ GeV^2

$|z|<0.35$

Will give an overview and main results of this analysis

M. Betancourt, R. Gran, RJH, A. Meyer (to appear)

Event-level data from the deuterium experiments has been lost

Ab initio flux estimates have poorly constrained systematics.

- Use published distributions in neutrino energy to determine flux self-consistently:

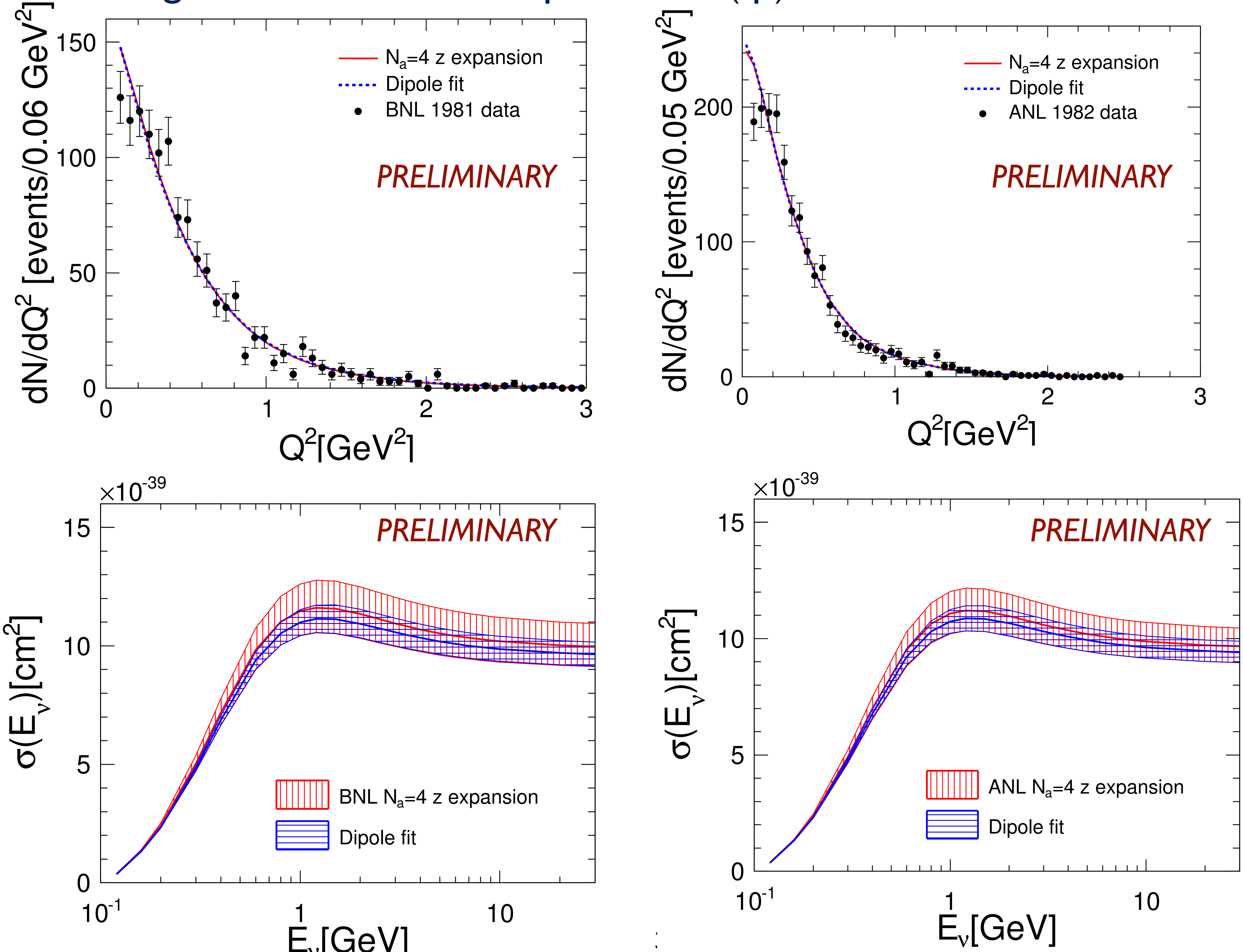
$$\Phi(E_\nu)dE_\nu = \frac{1}{\sigma(E_\nu, F_A)}\frac{dN}{dE_\nu}dE_\nu$$

- Fit to published Q^2 distributions to determine F_A

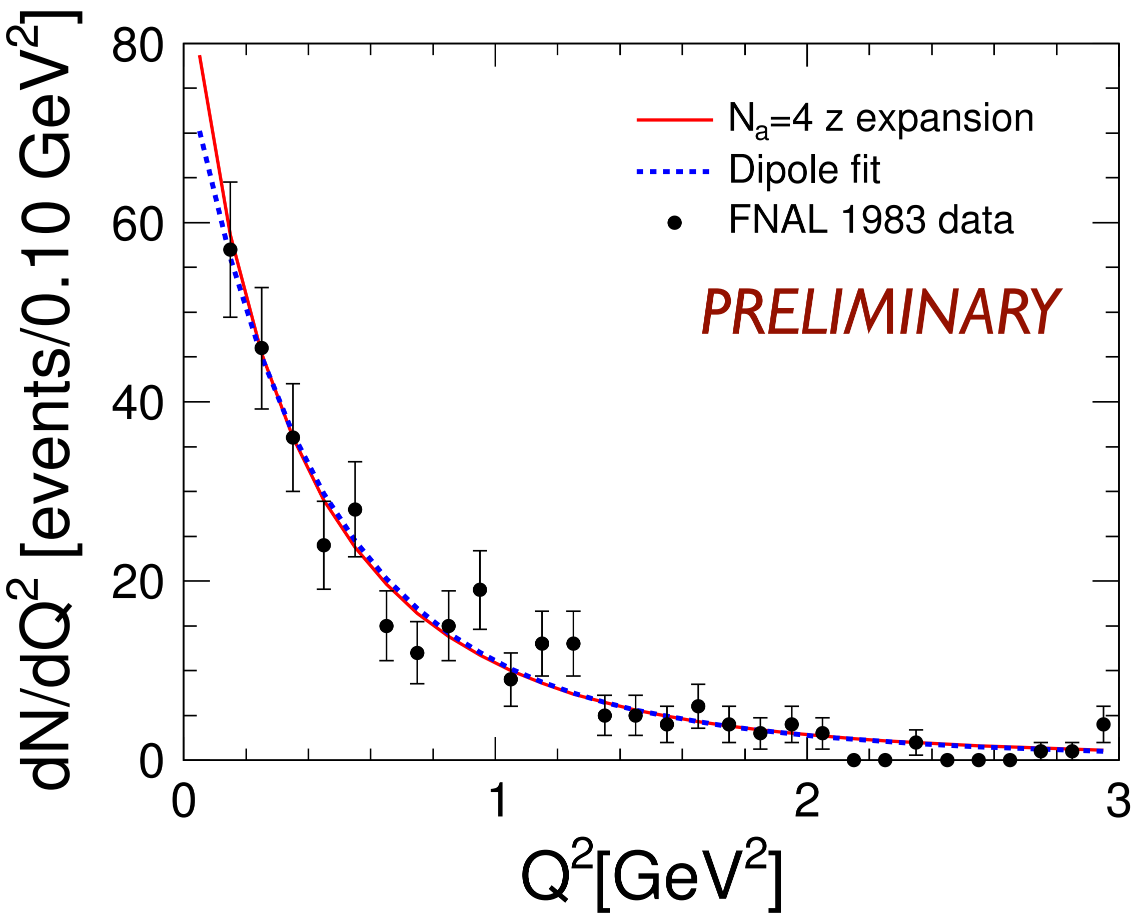
Reproduced results of original publications under same assumptions

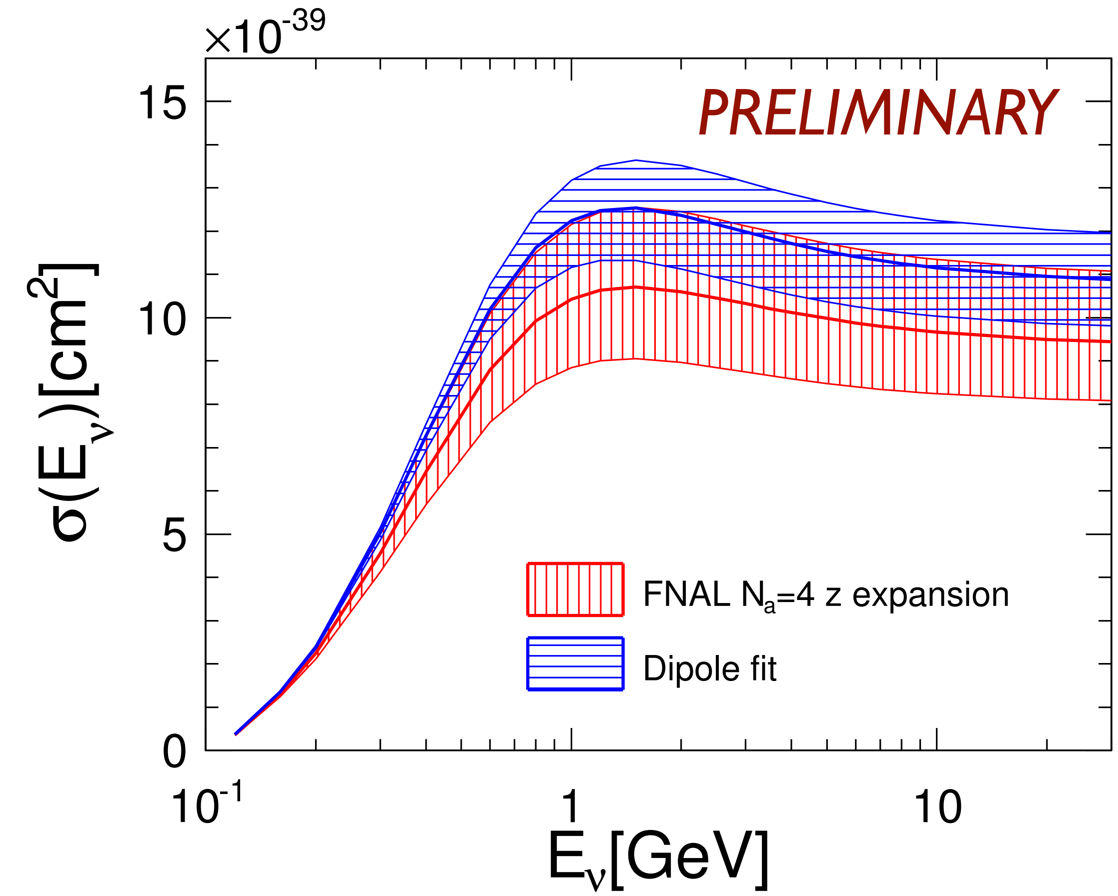
Replaced dipole F_A with model-independent z expansion (and updated other parameter values)

Binned log likelihood fit to z-expansion $F_A(q^2)$

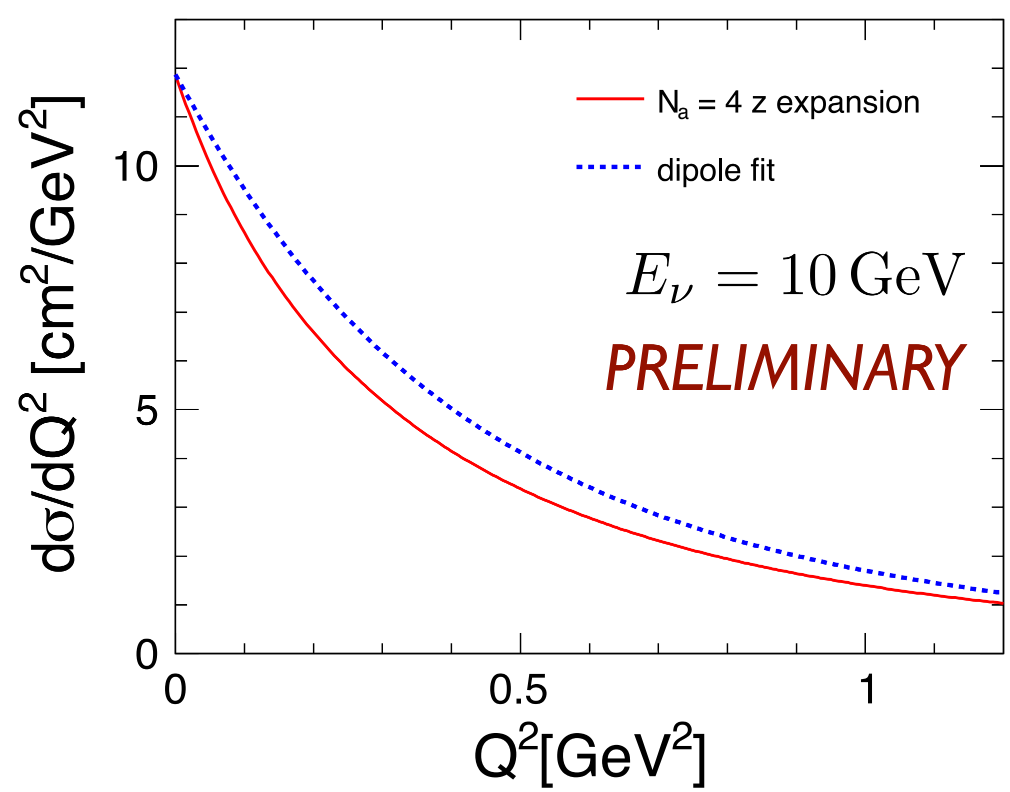


Dipole and z expansion yield different F_A

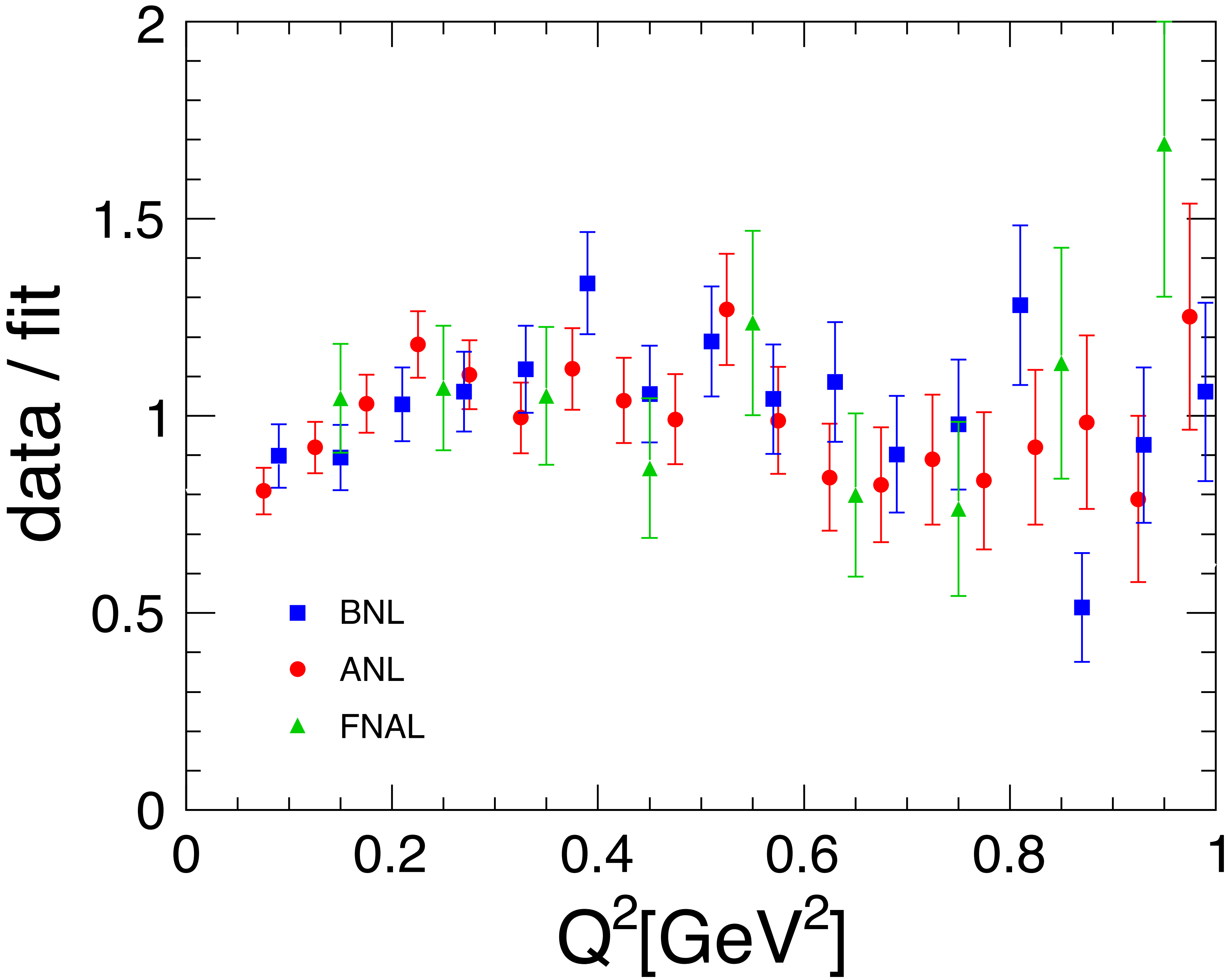




(recall floating normalization and self-consistent flux: different F_A can yield similar dN/dQ^2 in fit range)



Data are in tension with any F_A described by QCD



$\chi^2 = 30\ (16\,\mathrm{points,\ BNL})$

$\chi^2 = 32\ (19\,\mathrm{points,\ ANL})$

Possible correlated effect between datasets, including deficit at small Q^2

Revisit systematics:
- experimental acceptance/efficiency correction
- theoretical deuteron correction

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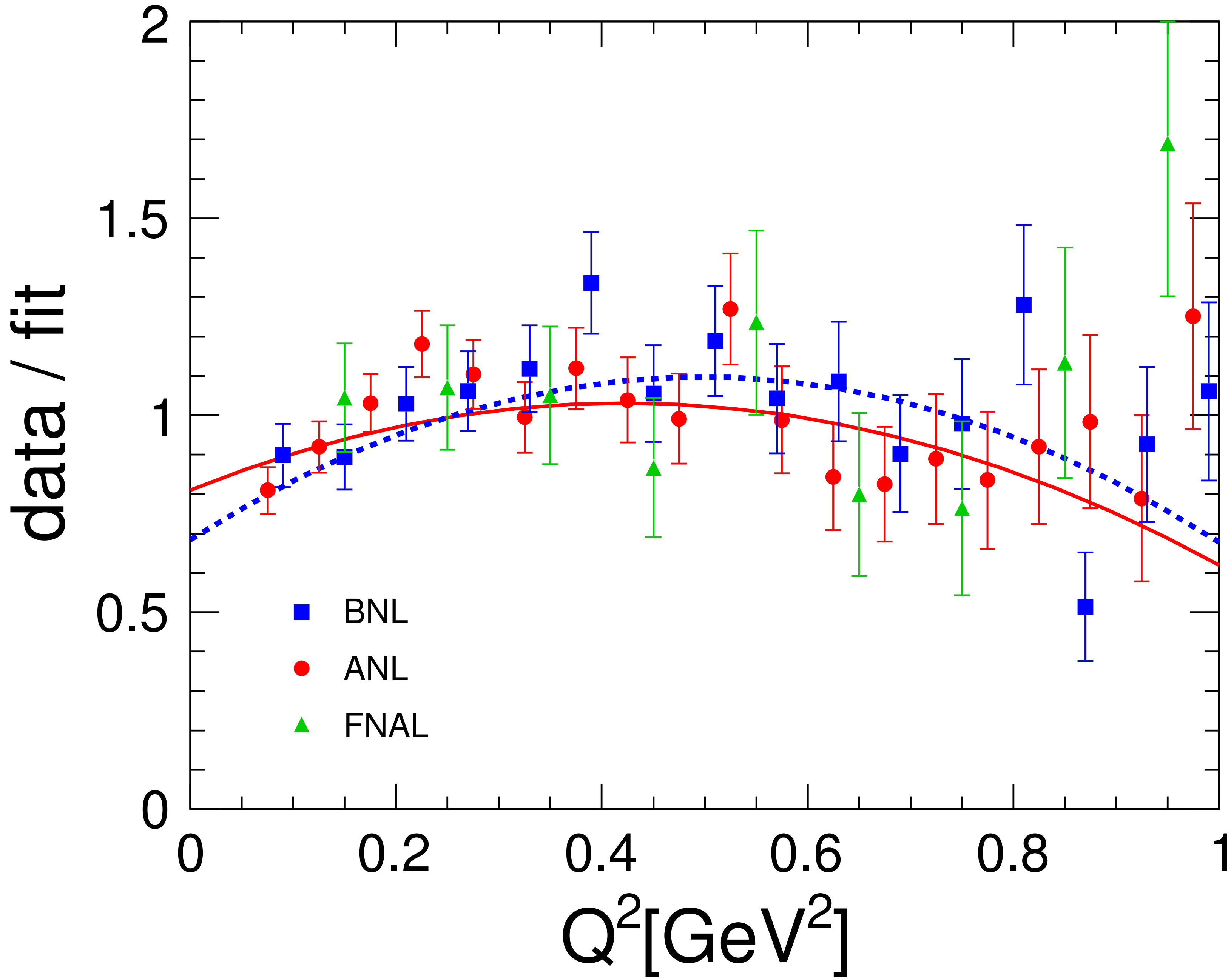

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Revisit systematics: - experimental acceptance/efficiency correction
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- experimental acceptance/efficiency correction

allow for correlated variation: η=0 ± 1

$$\frac{dN}{e(Q^2)} \to \frac{dN}{e(Q^2)+de(Q^2)} = \frac{dN}{e(Q^2)}\left(1+\eta_e\frac{de(Q^2)}{e(Q^2)}\right)^{-1}$$

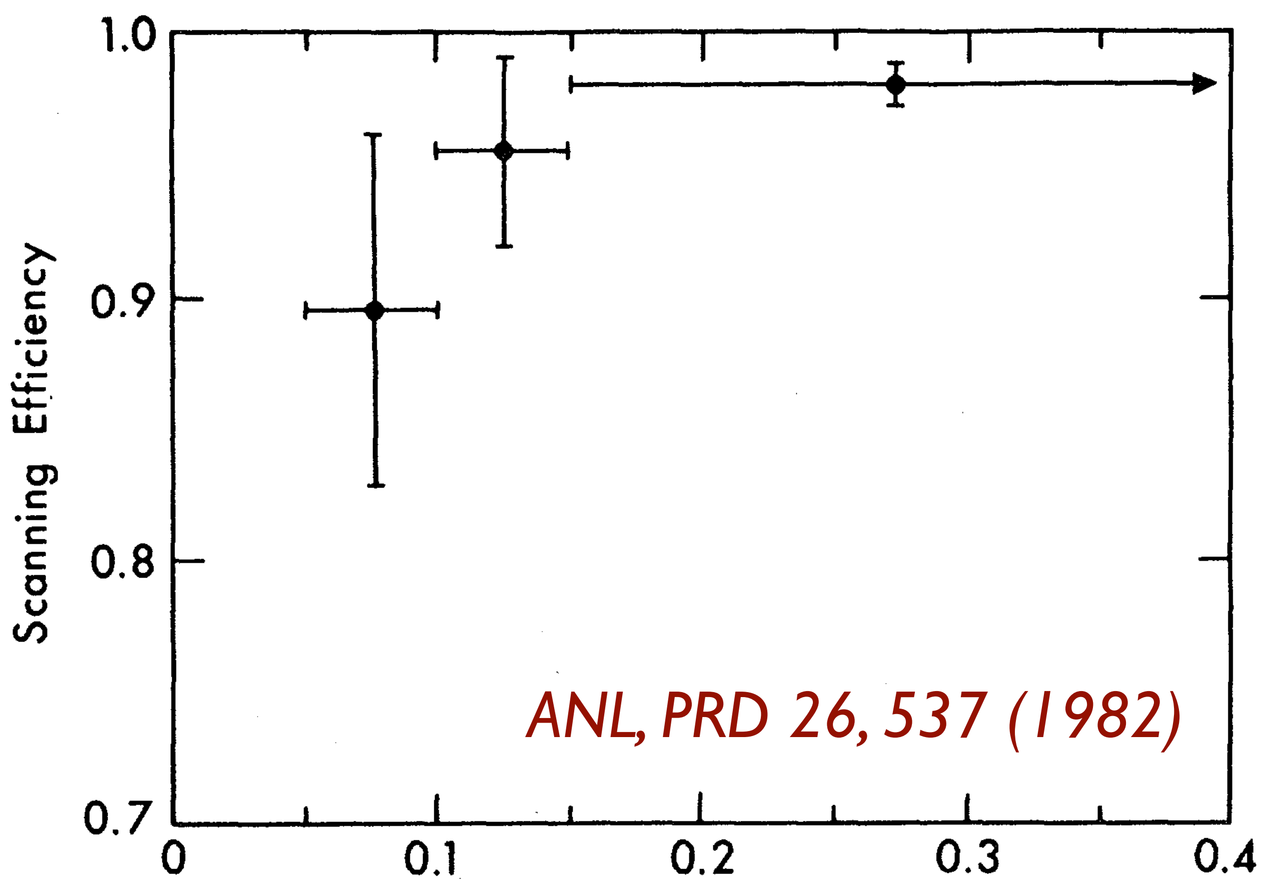
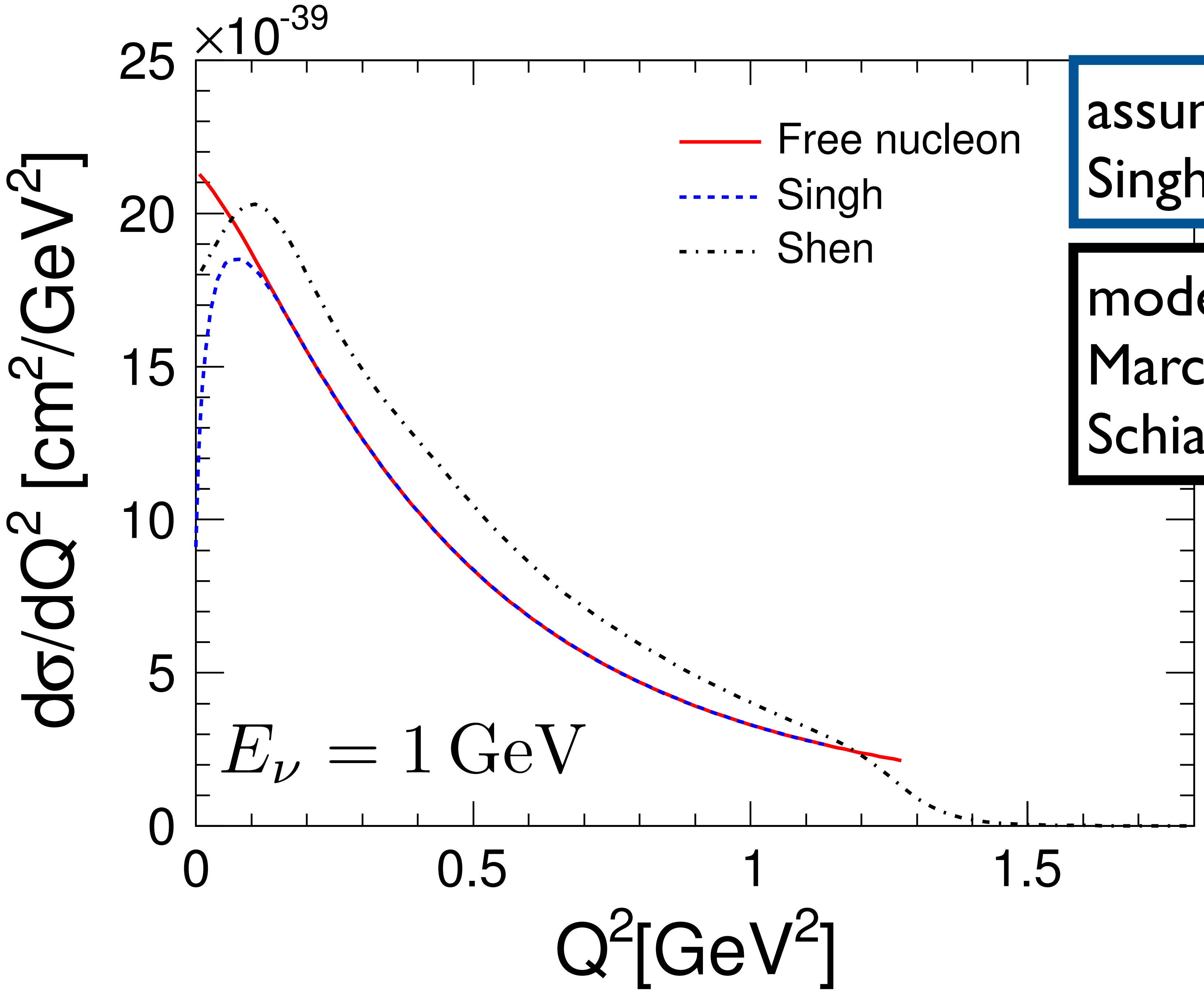


FIG. 1. Scanning efficiency as a function of momentum transfer squared.

data prefer η≠0 (ANL: η=-1.9, BNL: η=-1), but no significant improvement in fit quality

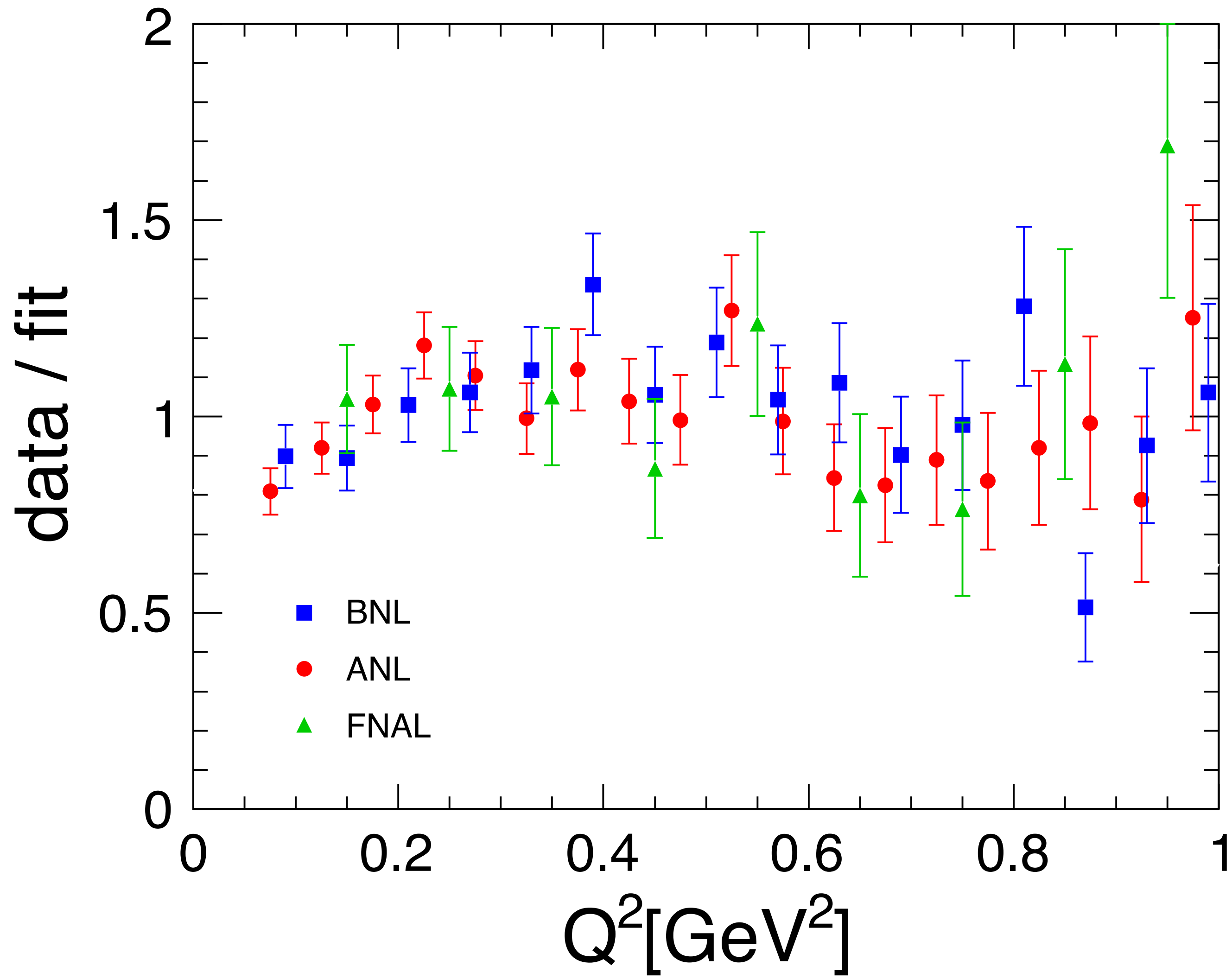
- theoretical deuteron correction



assumed in existing world averages: Singh, NPB 36, 419 (1972).

modern potential model: Shen, Marcucci, Carlson, Gandolfi, Schiavilla (1205.4337)

An open problem to quantify uncertainty, especially at larger energy



In final determination :

- joint fit to all data (ANL, BNL, FNAL)

- include correlated efficiency correction (for each dataset)

- include additional uncorrelated error to achieve X^2/d.o.f. = 1 ($\delta N/N \approx 10\%$)

Deuterium constraints on F_A

$$F_A(q^2) = \sum_k a_k [z(q^2)]^k$$

Complete description: coefficients, errors and correlations

$$(a_1, a_2, a_3, a_4) =$$
$$(2.29^{+0.13}_{-0.13}, -0.6^{+1.0}_{-1.0}, -3.7^{+2.5}_{-2.6}, 2.2^{+2.7}_{-2.7})$$

$$C_{ij} = \begin{pmatrix} 1 & 0.351 & -0.679 & 0.611 \\ 0.351 & 1 & -0.898 & 0.369 \\ -0.679 & -0.898 & 1 & -0.686 \\ 0.611 & 0.369 & -0.686 & 1 \end{pmatrix}$$

Derived observables: 1) axial radius

$$\frac{1}{F_A(0)} \frac{dF_A}{dq^2}\bigg|_{q^2=0} \equiv \frac{1}{6} r_A^2$$

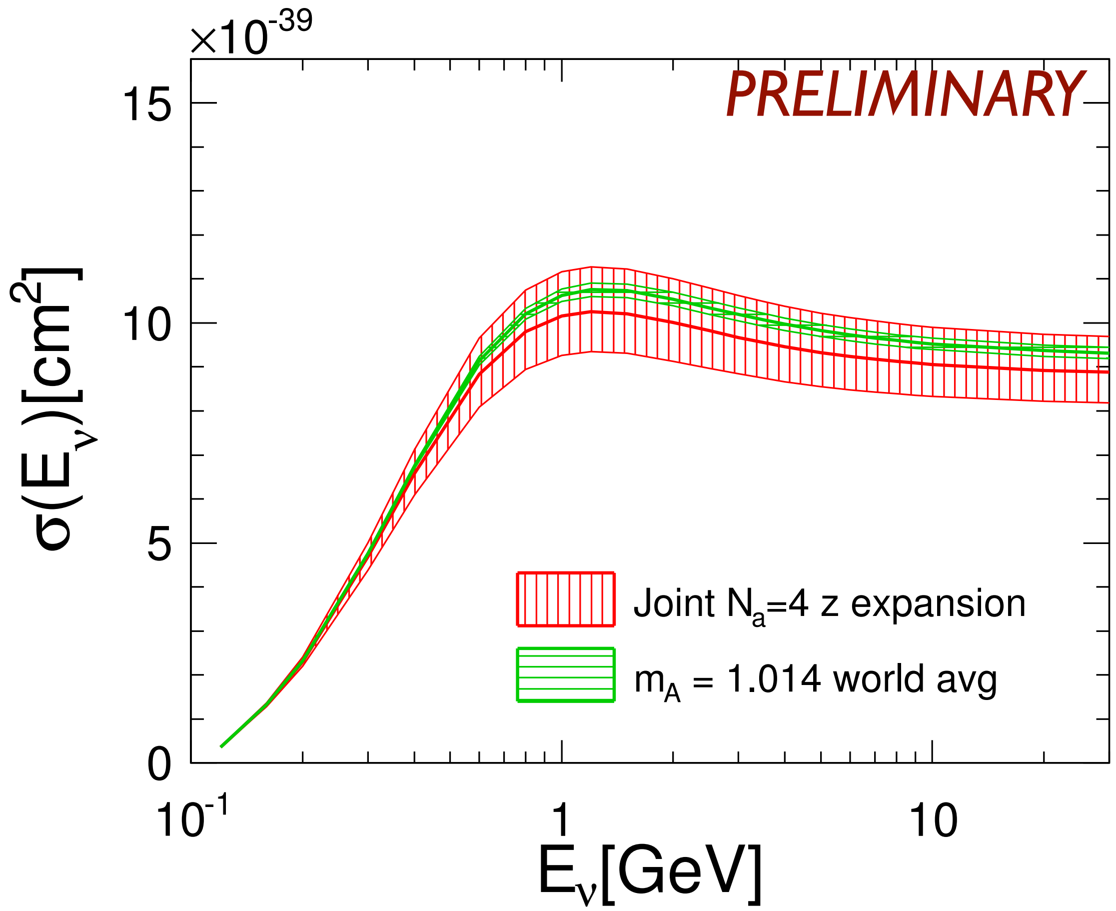
$$r_A^2 = 0.47(31)\,\mathrm{fm}^2$$

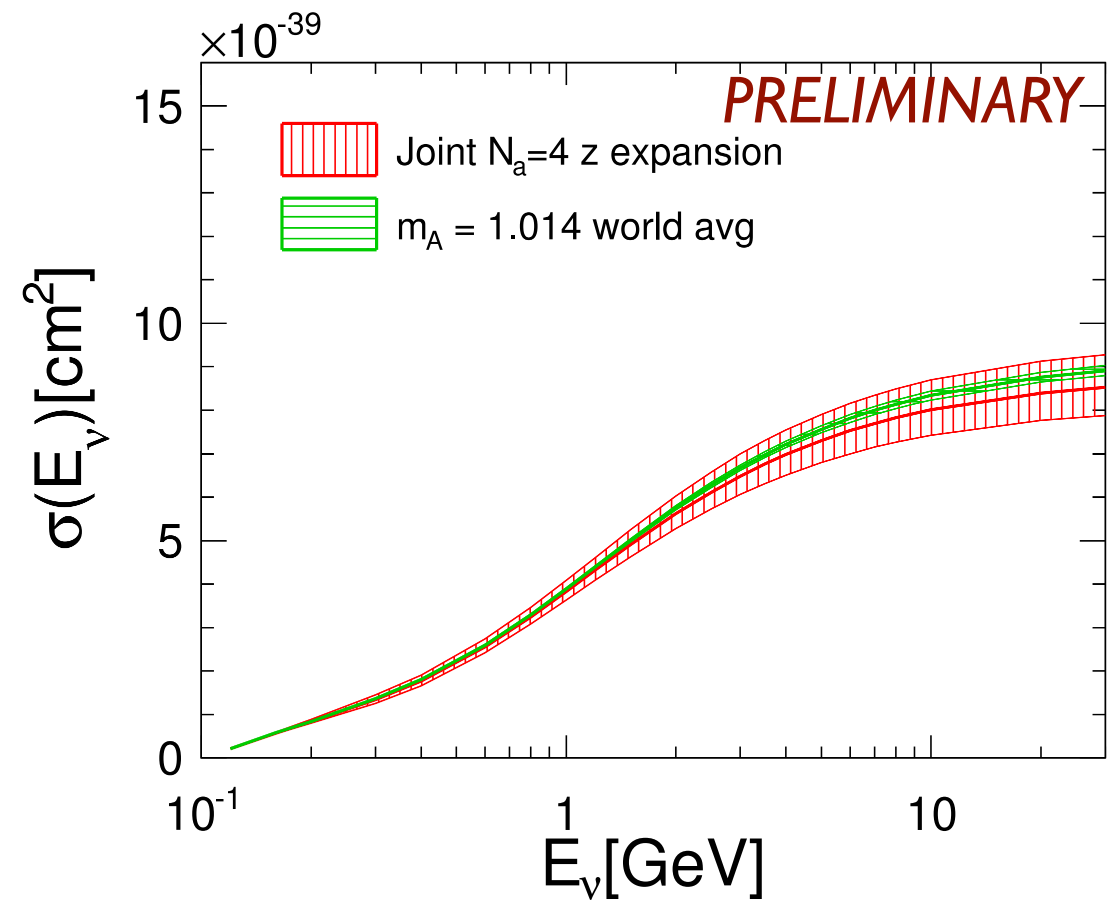
PRELIMINARY

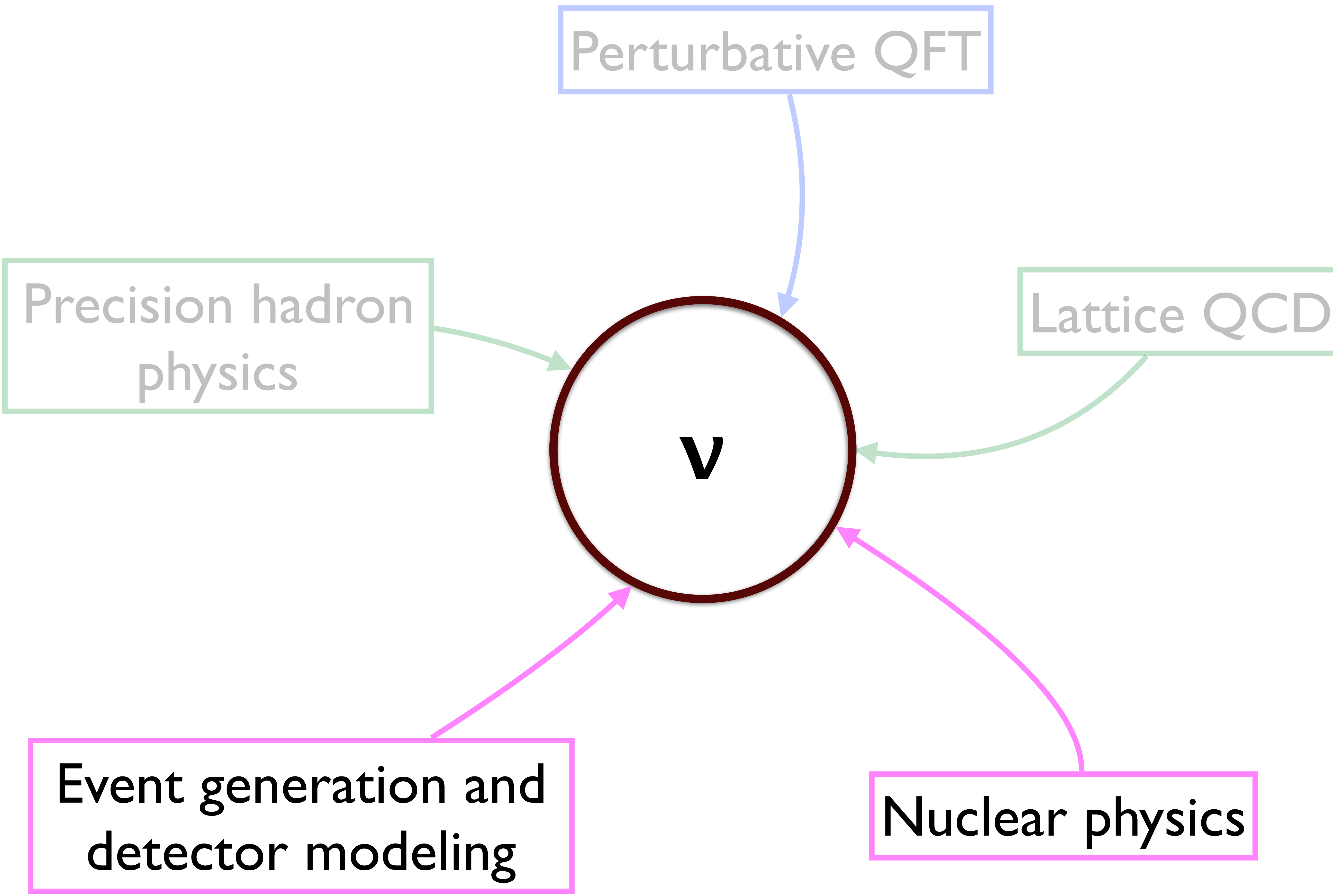
- order of magnitude larger uncertainty compared to dipole fits

- impacts comparison to other data, e.g. pion electroproduction, muon capture

Derived observables: 2) neutrino-nucleon quasi elastic cross sections






Perturbative QFT
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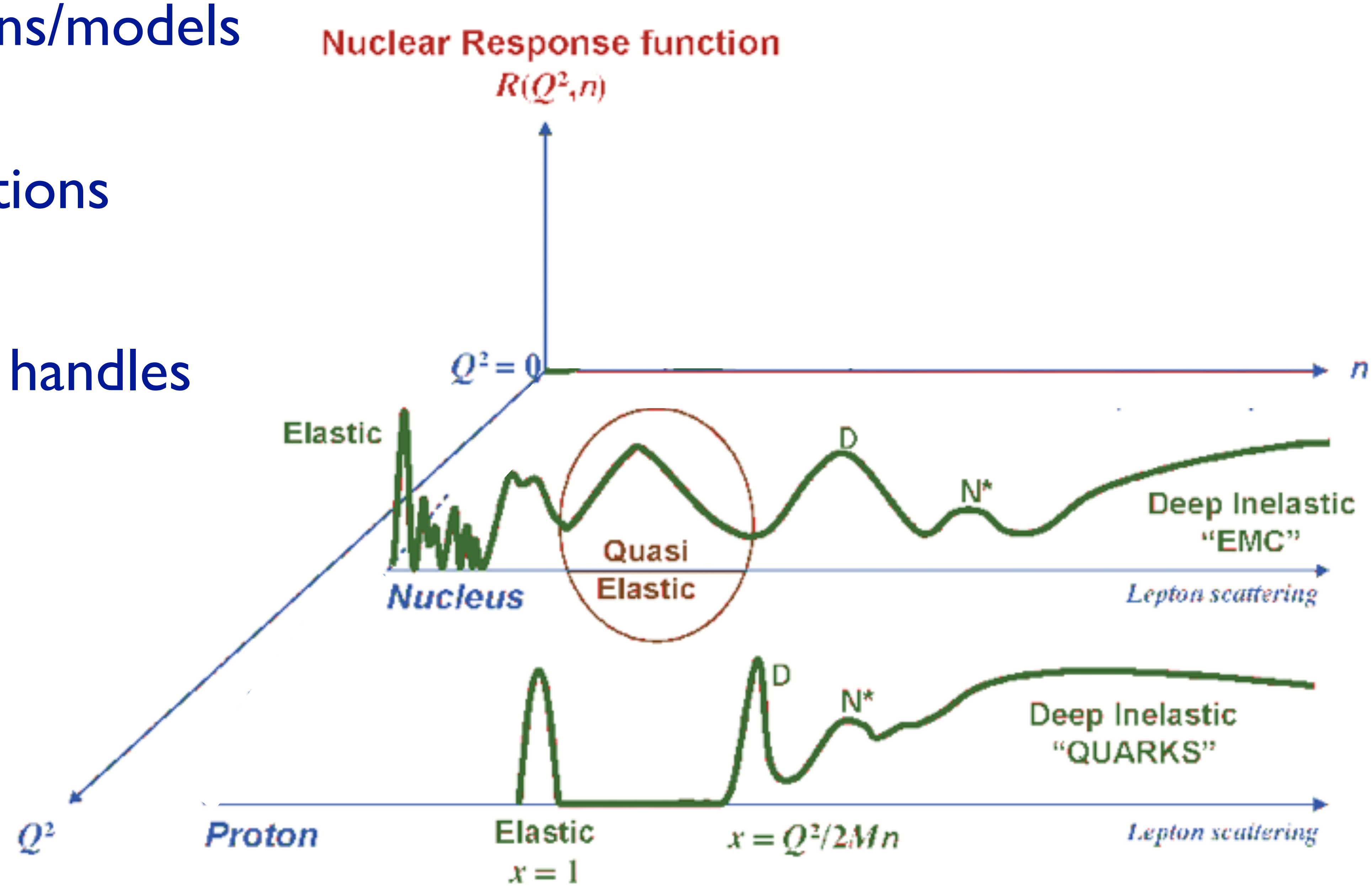
ν
Event generation and detector modeling
Nuclear physics

Rigorous nucleon-level inputs (with error bars!) provide foundation for neutrino-nucleus predictions

- ab initio calculations/models

- clever event selections

- new experimental handles

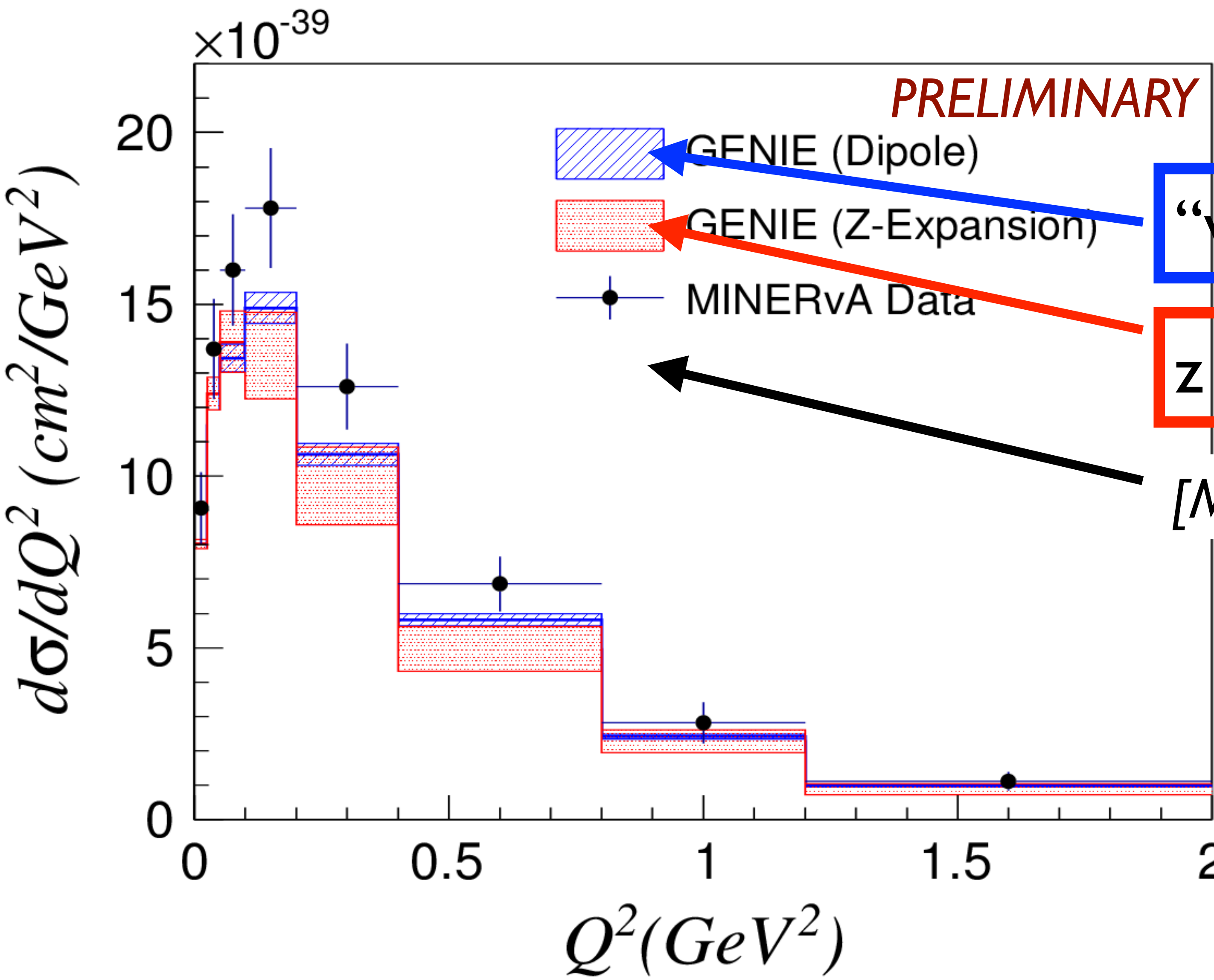


- ab intio calculations/models

New module for z expansion and reweighting in GENIE event generator

A. Meyer

Fit to MINERvA carbon data



"world average dipole"

z expansion constrained by deuterium

[Minerva PRL 111, 022502 (2013)]
with 2015 updated flux

⇒ Robust constraints on nuclear parameters (cf. parton distribution function determination at colliders)

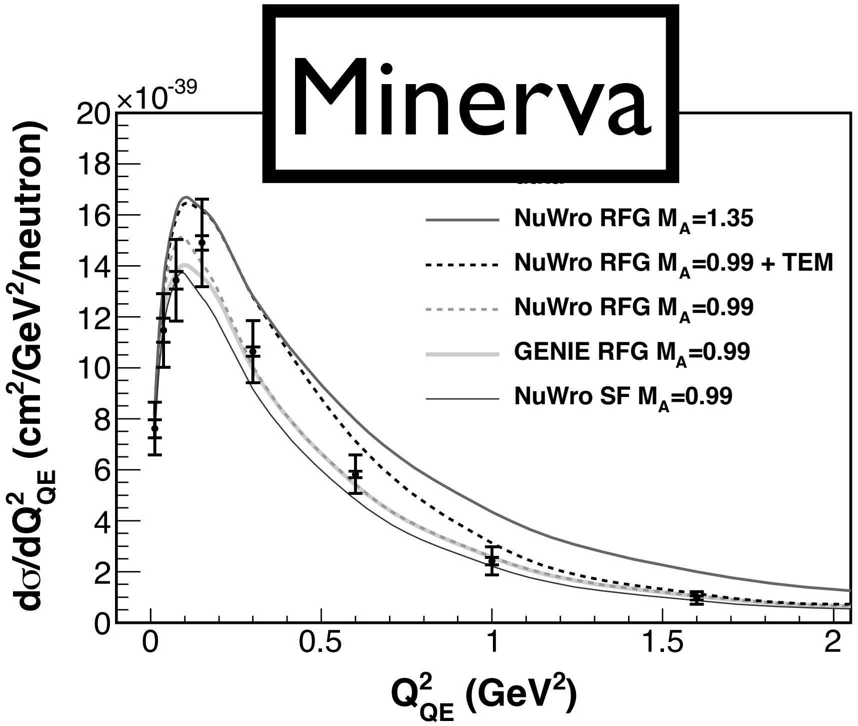
⇒ Robust errors propagated to oscillation observables

- ab intio calculations/models

Can we constrain a simple nuclear model for two-body contributions ?

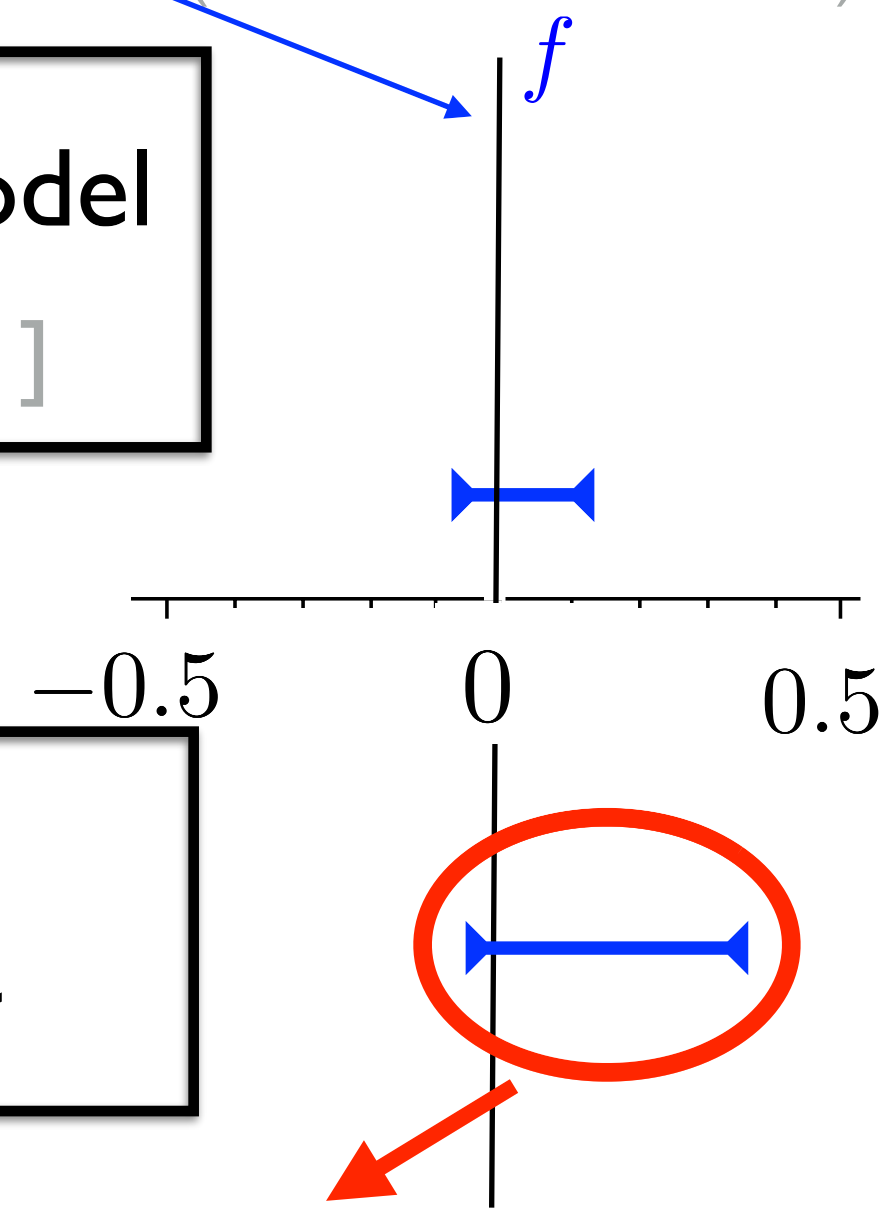
$$\sigma = \sigma_{1-\text{body}} + f\sigma_{2-\text{body}}$$

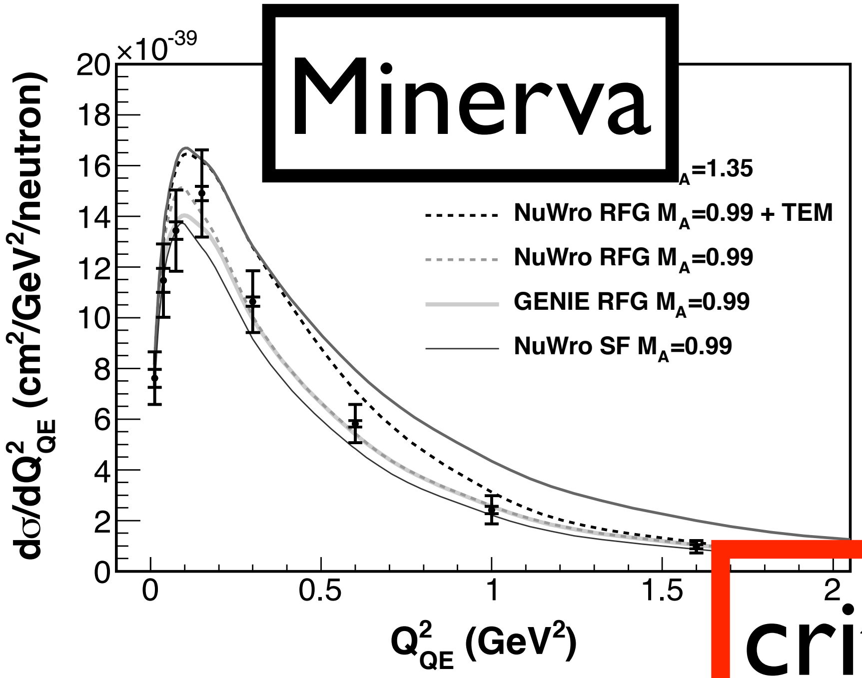
(GENIE MEC model)



+ F_A = dipole model

[m_A=1.01(2)]





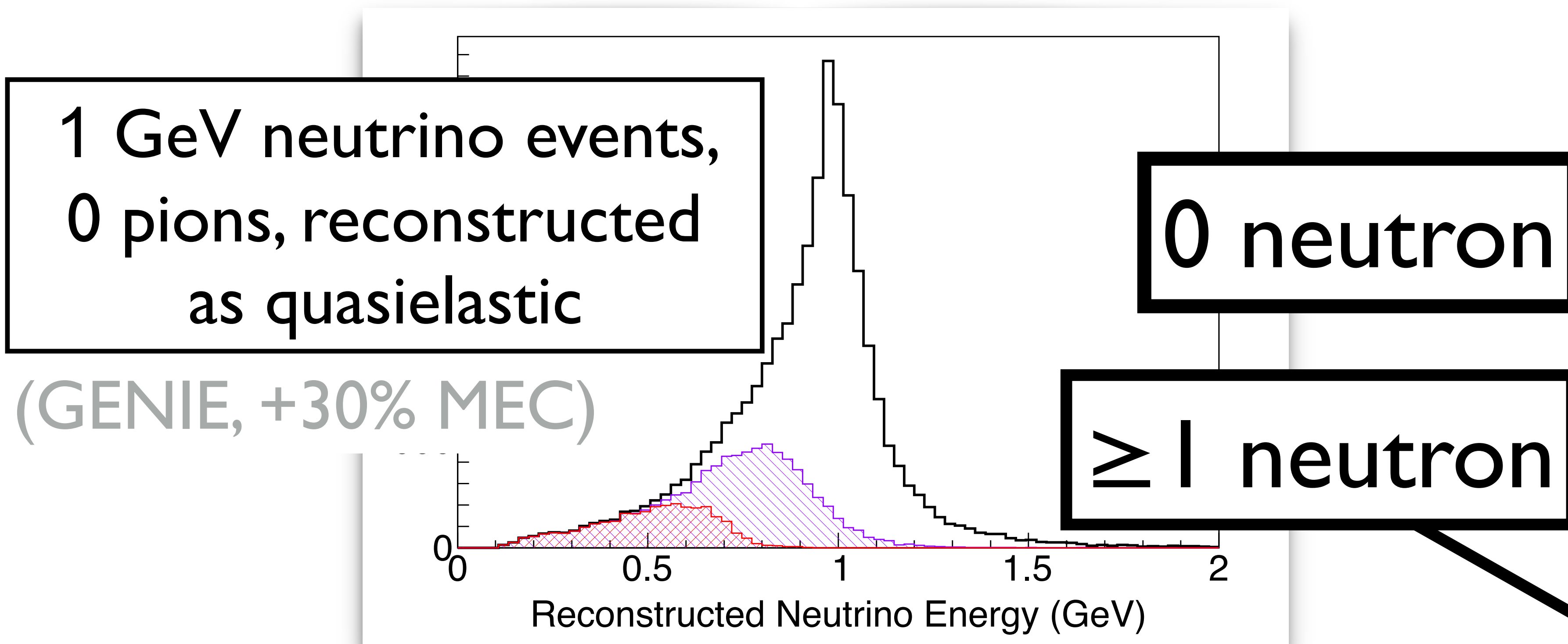
+ F_A = model-independent

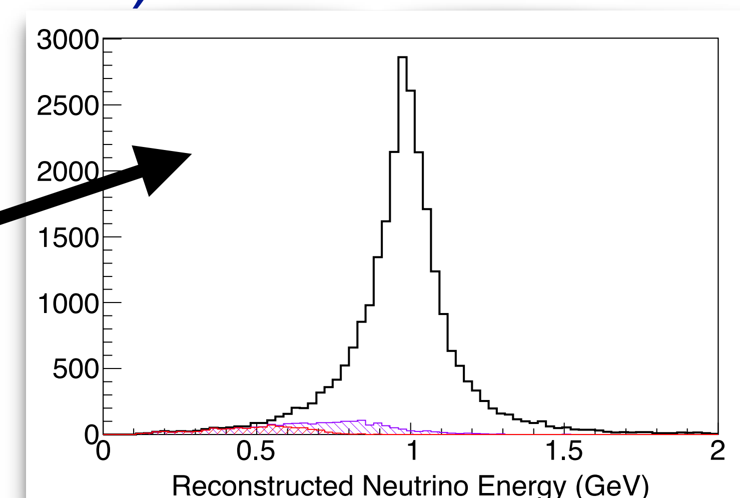
critical to account for nucleon-level errors

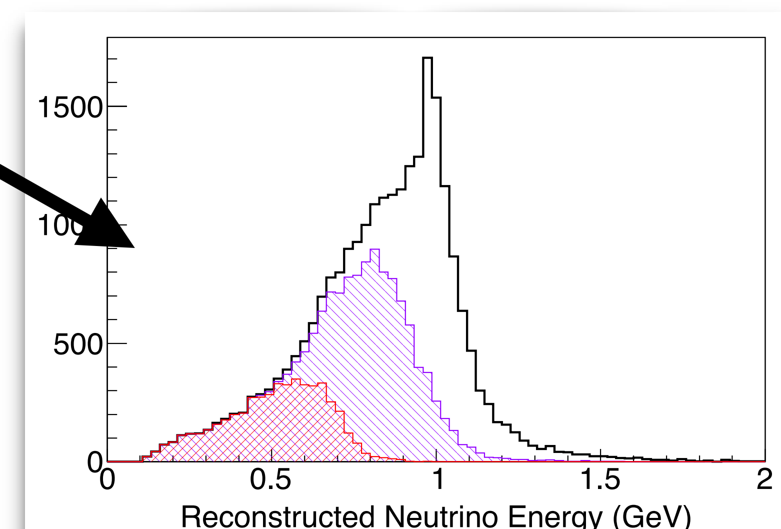
- clever event selections/new experimental handles

cf. colliders: define event classes to isolate underlying parton mechanisms (vector boson fusion, gluon fusion,…)

for neutrinos: define event classes with (in)sensitivity to underlying nucleon-level mechanisms (multinucleon processes,…)







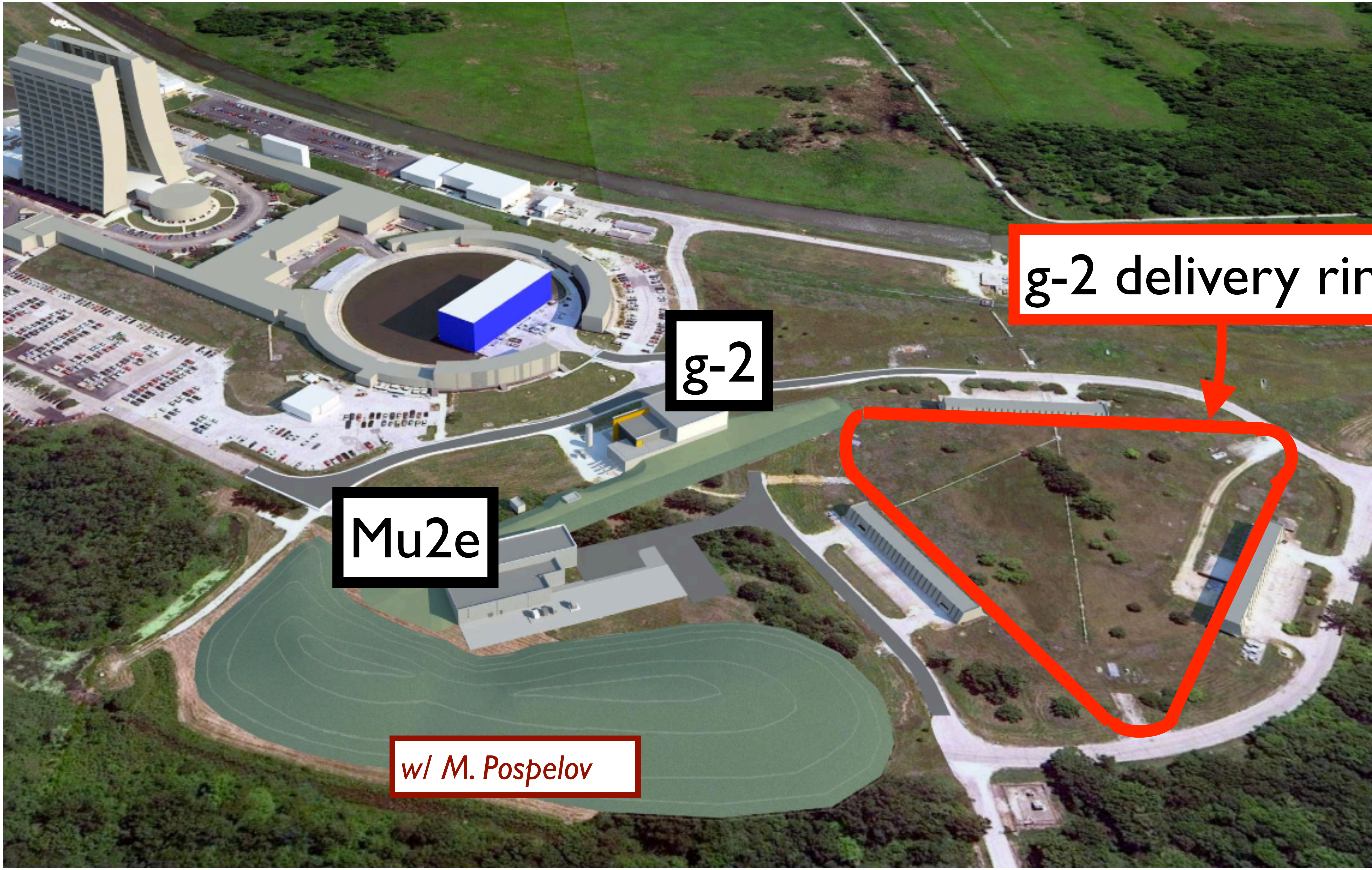
C. Blanco, M. Wetstein, RJH

Capitalize on new detector technologies

- final state protons in LArTPC
- final state neutrons (ANNIE)
- simple flux (stored muons); multiple fluxes ("nuPRISM"), …

Calibrate nuclear physics in known flux? (stored muon neutrino beam)

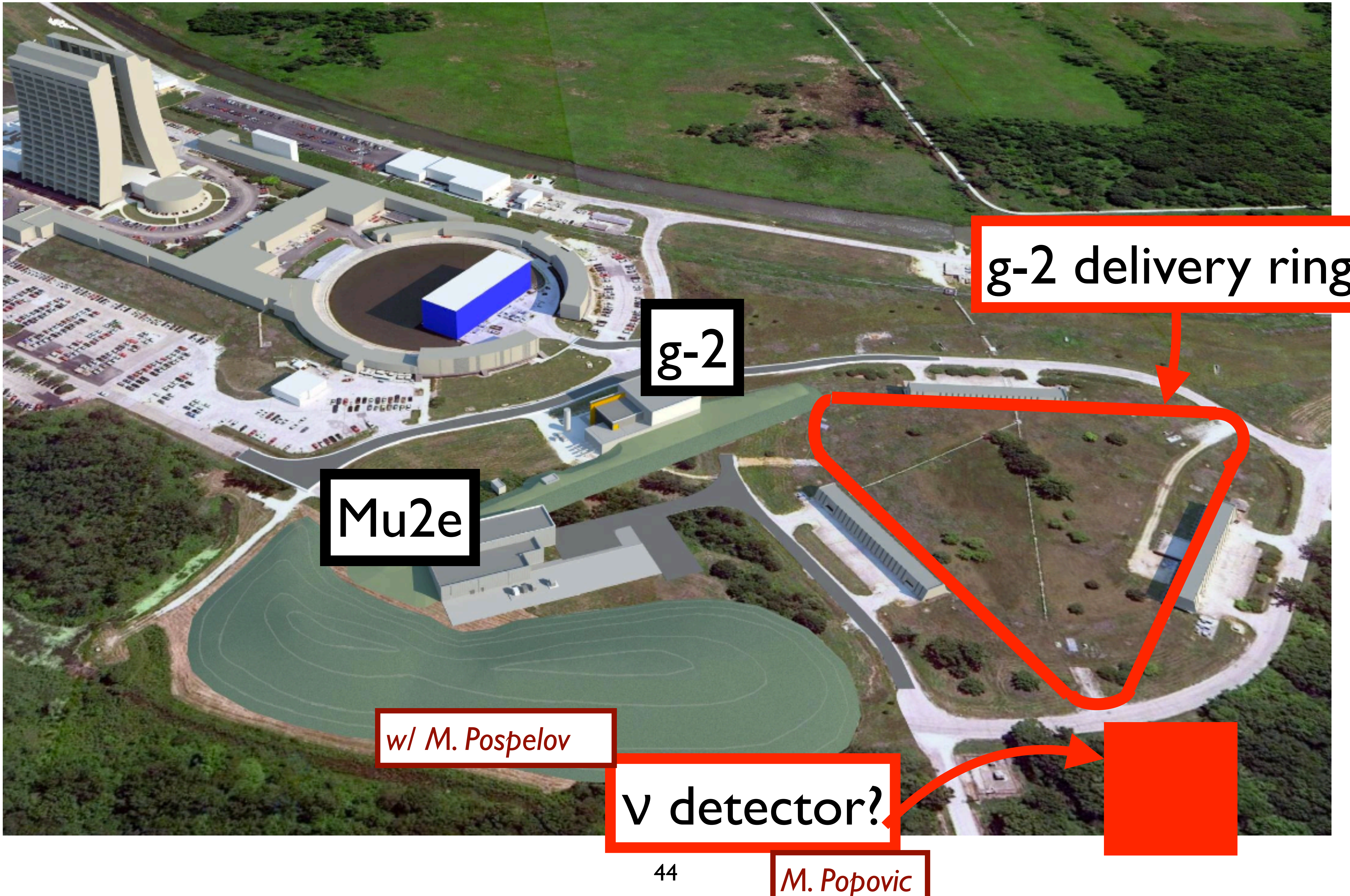
Also strong motivations for new elementary target experiments



M. Popovic

Calibrate nuclear physics in known flux? (stored muon neutrino beam)

Also strong motivations for new elementary target experiments



Calibrate nuclear physics in known flux? (stored muon neutrino beam)

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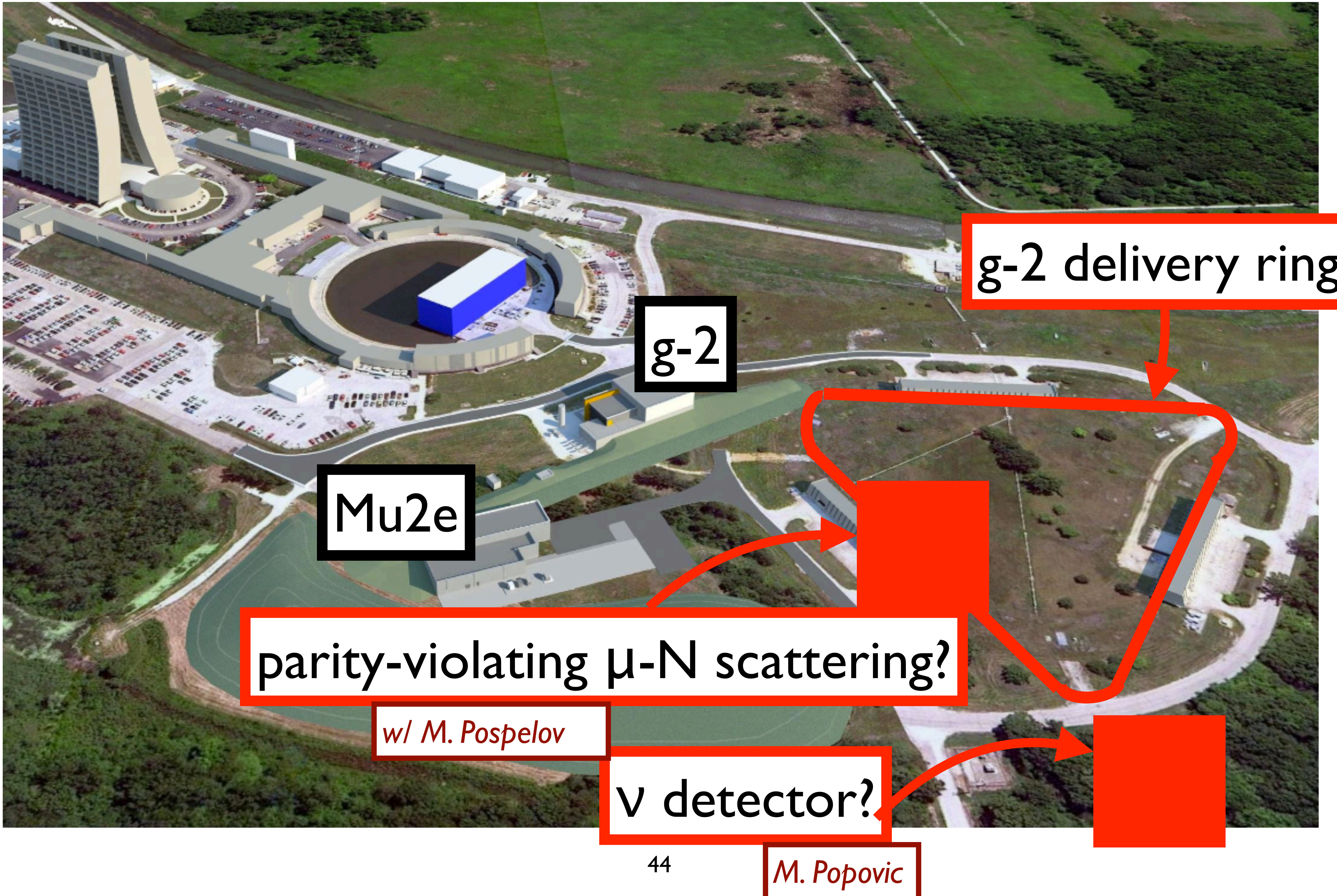

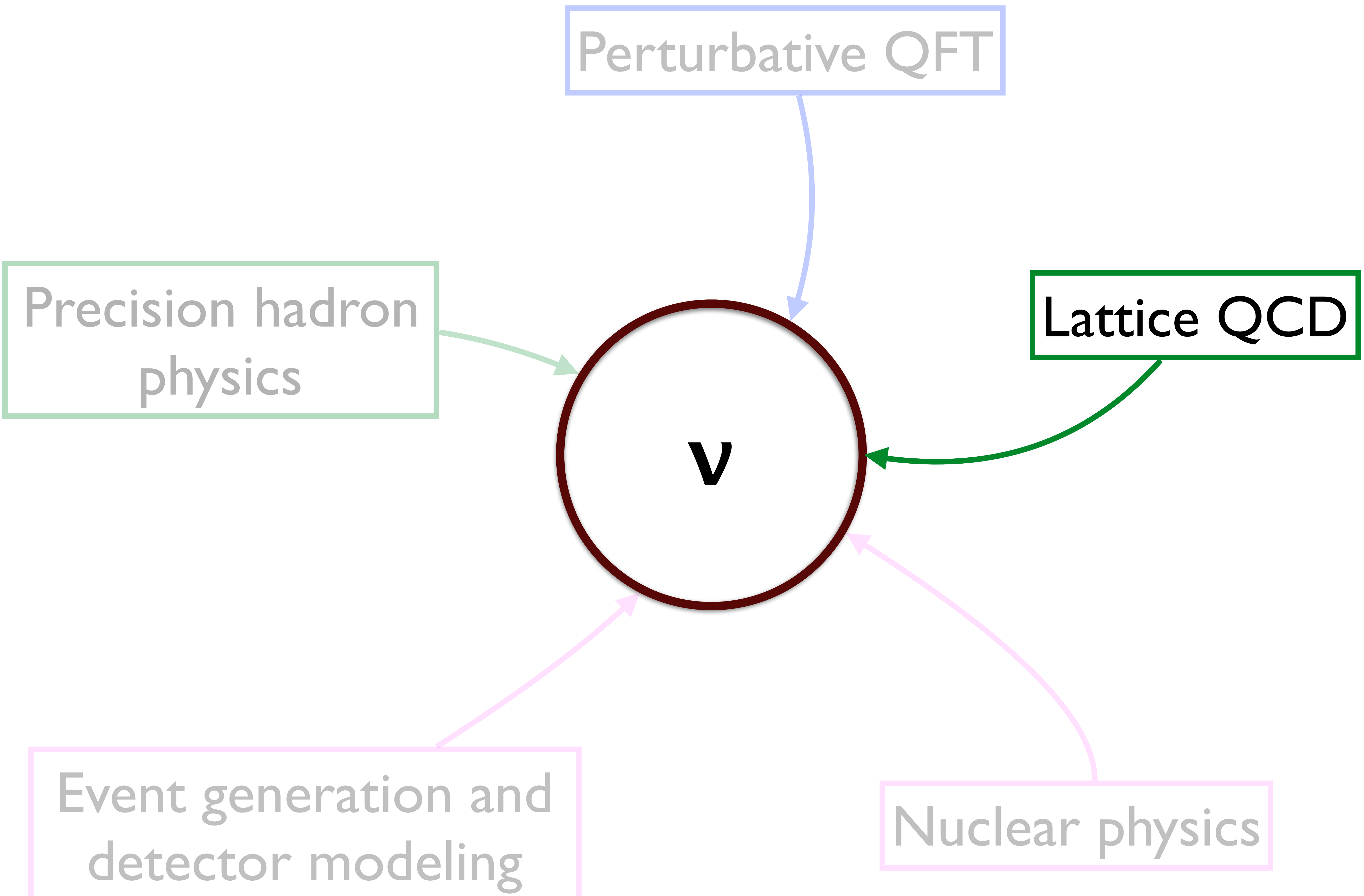
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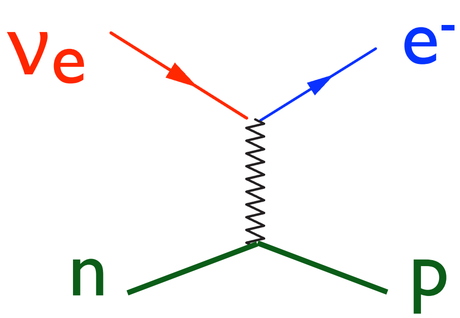
Lattice QCD can constrain nucleon-level amplitudes from first principles



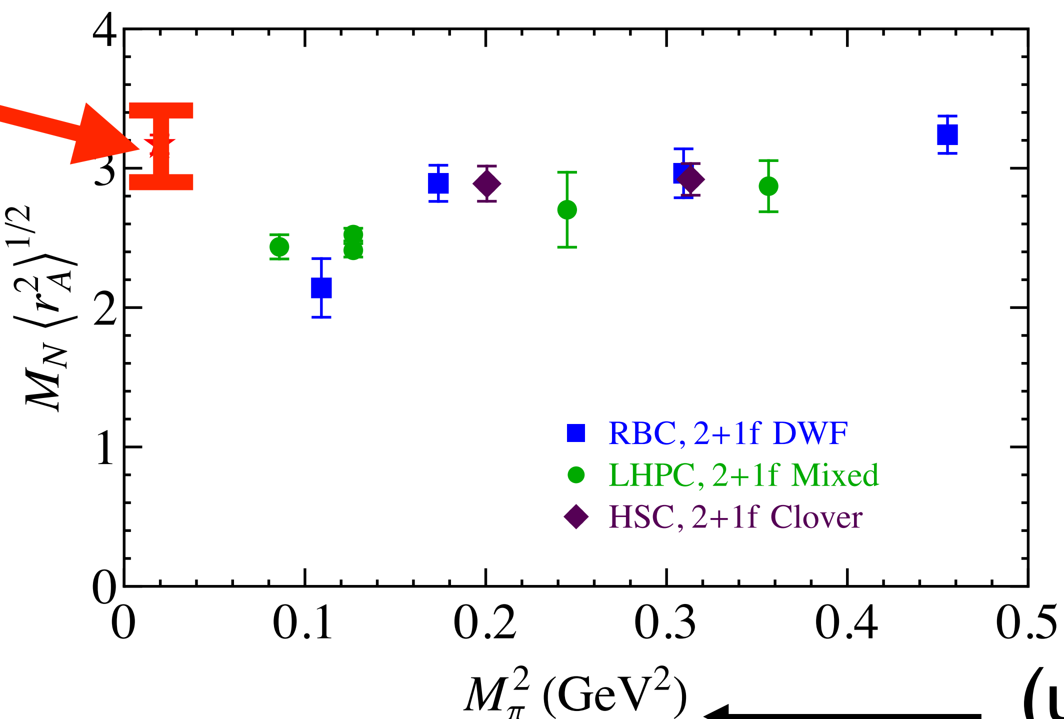
$$\sigma(\nu n \to ep) = |\cdots F_A(q^2) \cdots|^2$$

A prime target is the nucleon axial form factor

deuterium

illustrative:
dipole m_A=1.0(1)

$$\boxed{\left.\frac{dF_A}{dq^2}\right|_{q^2=0} \propto r_A^2}$$



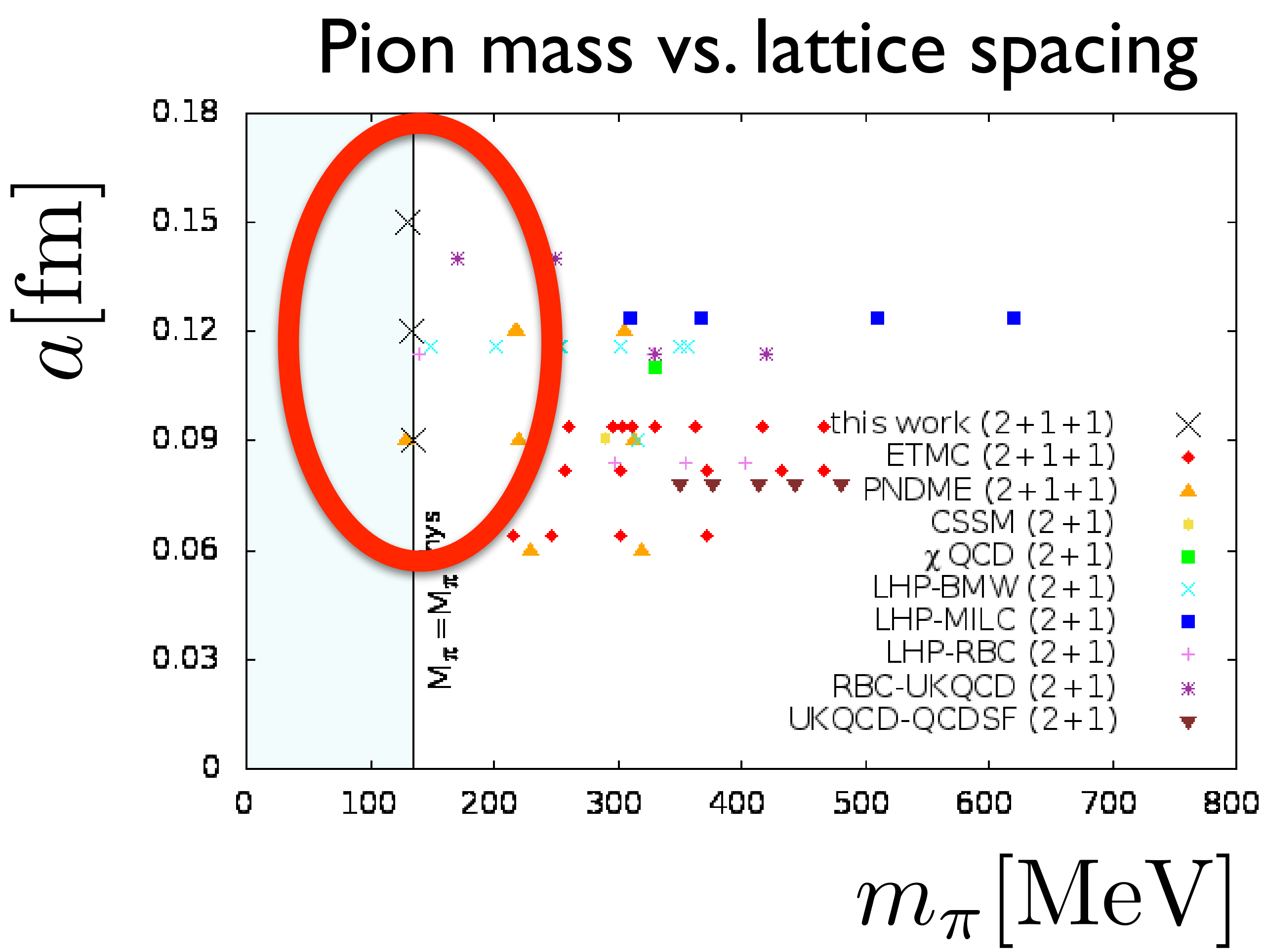
compilation from
Lin and Cohen 1104.4319

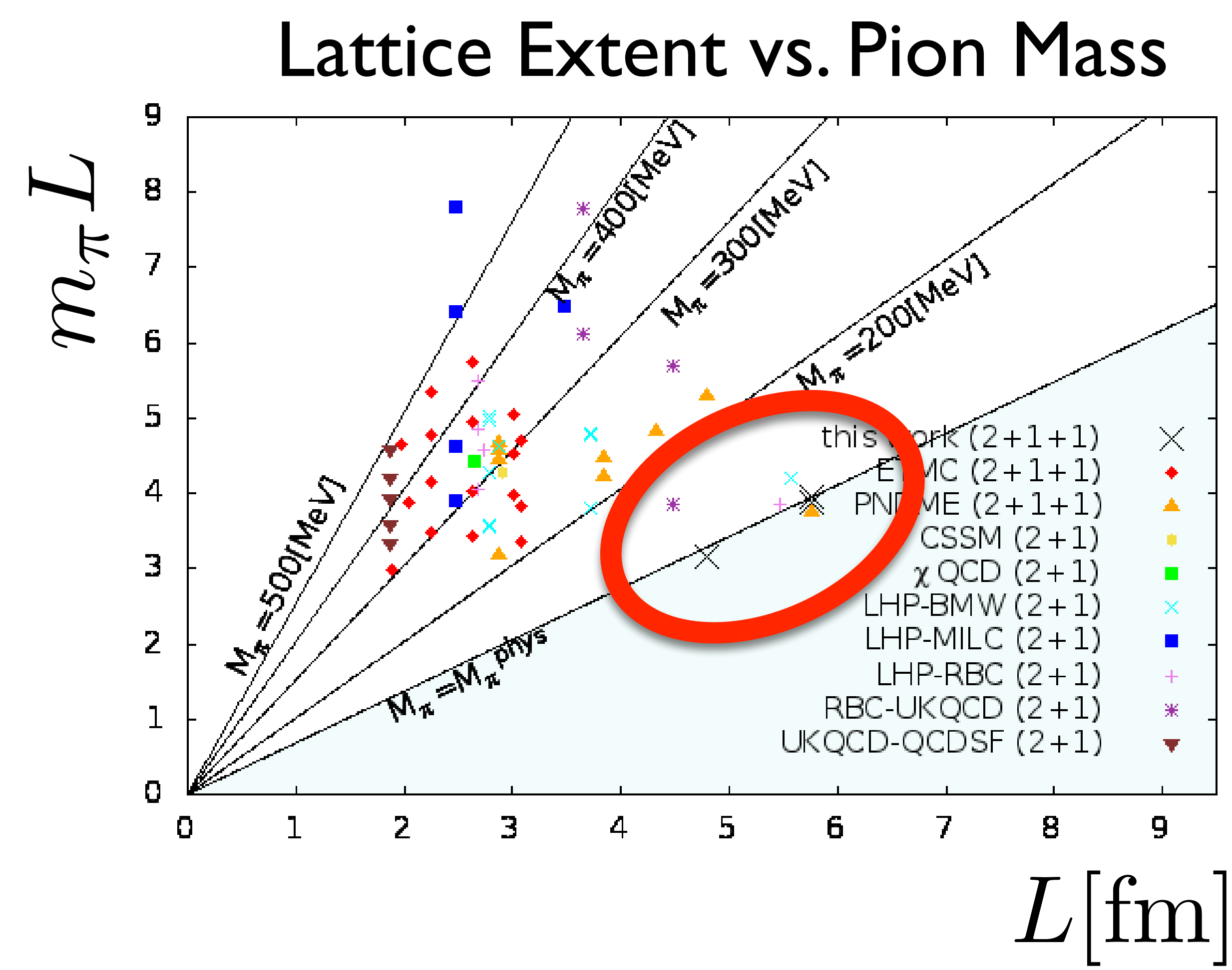
(unphysical) pion mass

Lattice QCD is poised to compete with deuterium data.

Need lighter quarks, bigger and finer lattices

A. Meyer, A. Kronfeld, RJH, Fermilab lattice and MILC collaborations

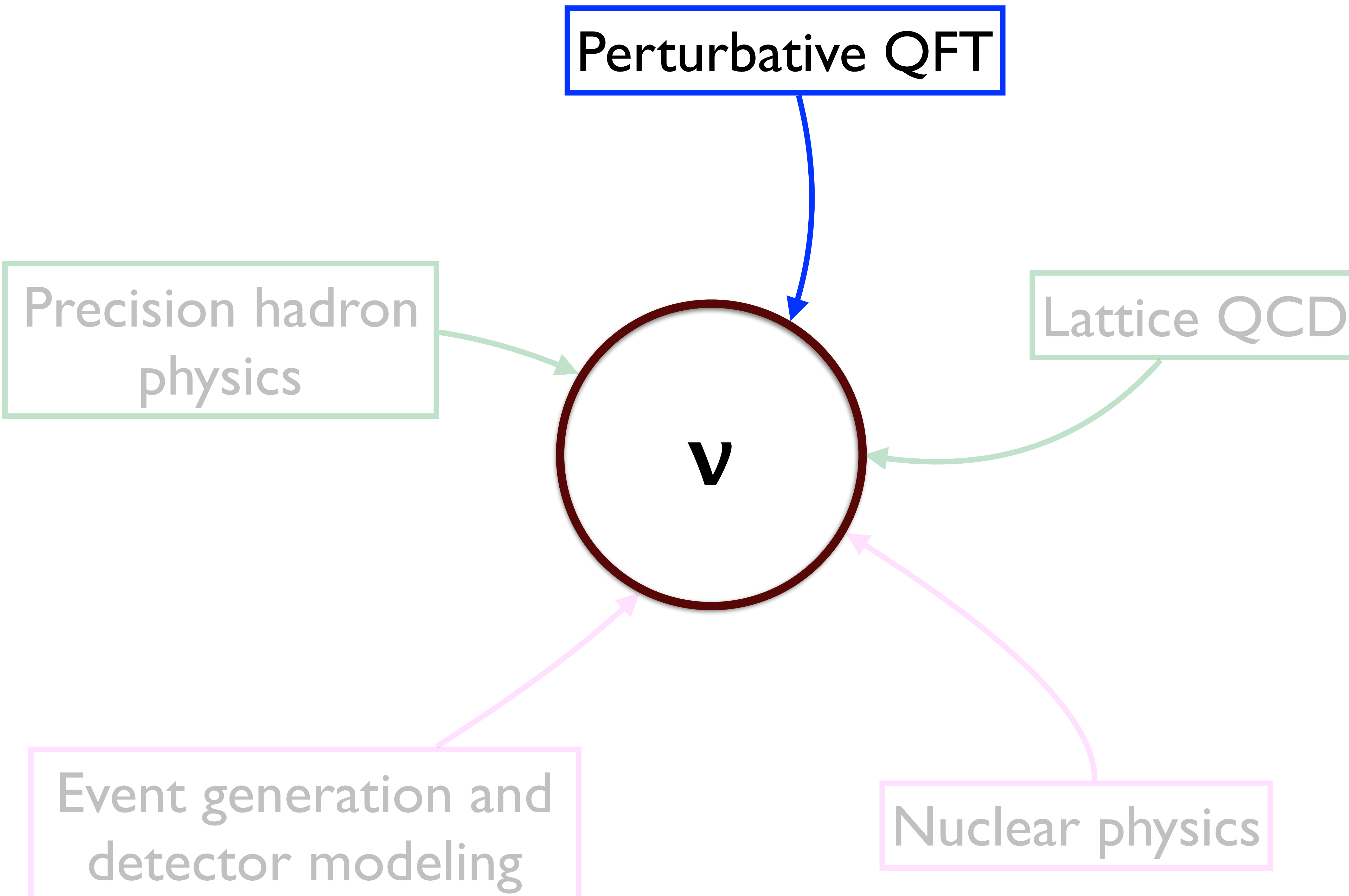




Big lattices, multiple spacings, physical quark masses

<u>Other targets</u>: neutral currents; resonance couplings and form factors; pion final states

<u>Advantages</u>: independent of detector-dependent radiative corrections and nuclear effects (and for lattice QCD: no underground safety hazard)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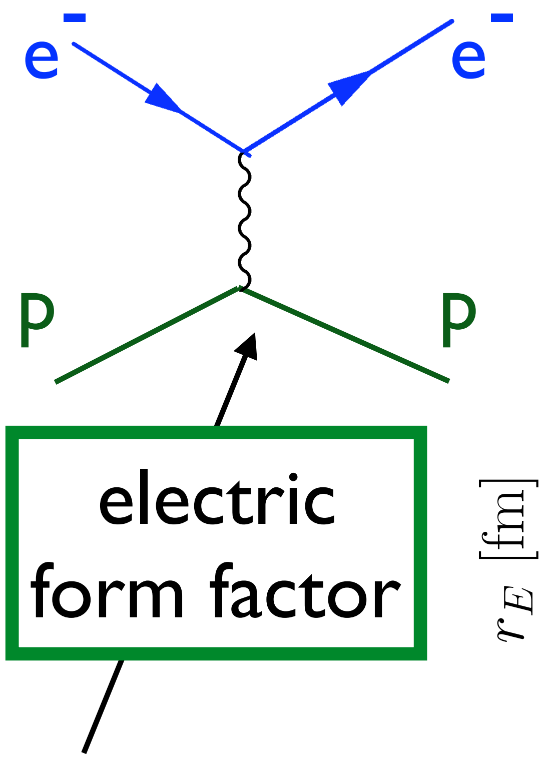
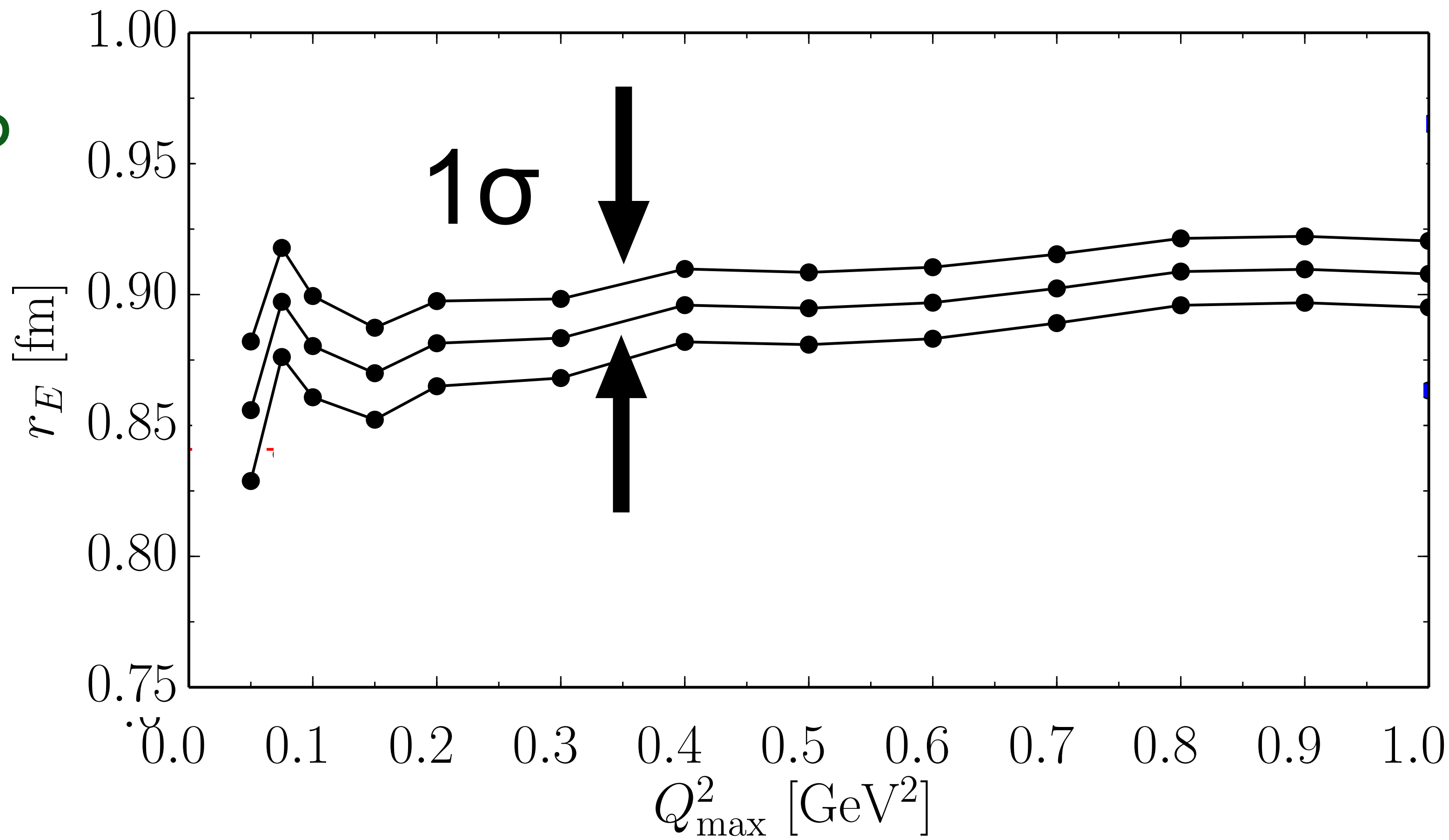
New analysis: G. Lee, J. Arrington, RJH 1505.01489

World e-p scattering dominated by 2010 MAMI A1 dataset: $0 < Q^2 < 1$ GeV^2 ($|z|<0.32$)



$$\frac{dF_E}{dq^2} \propto r_E^2$$



- Unexpected Q^2 dependence of extracted radius, and potentially large radiative corrections

- Work in progress to implement complete radiative corrections

- For both e-p and ν-N: large logarithms upset naive perturbation theory (especially important for ν_e/ν_μ ratios)

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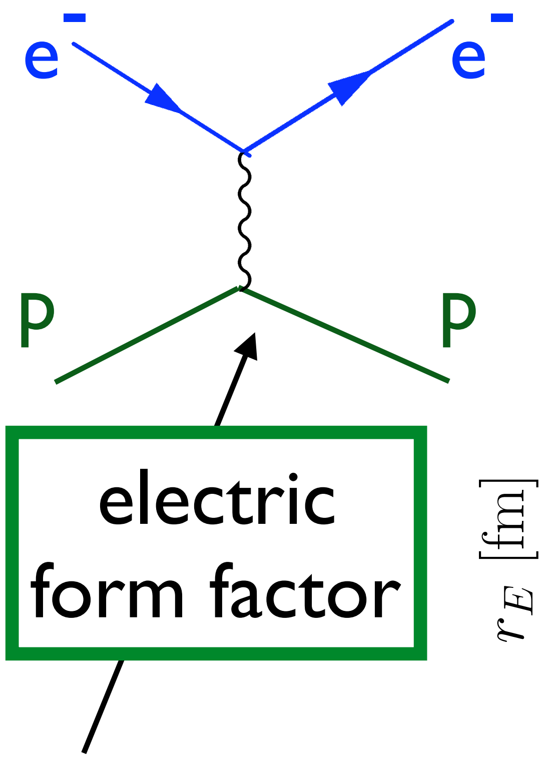

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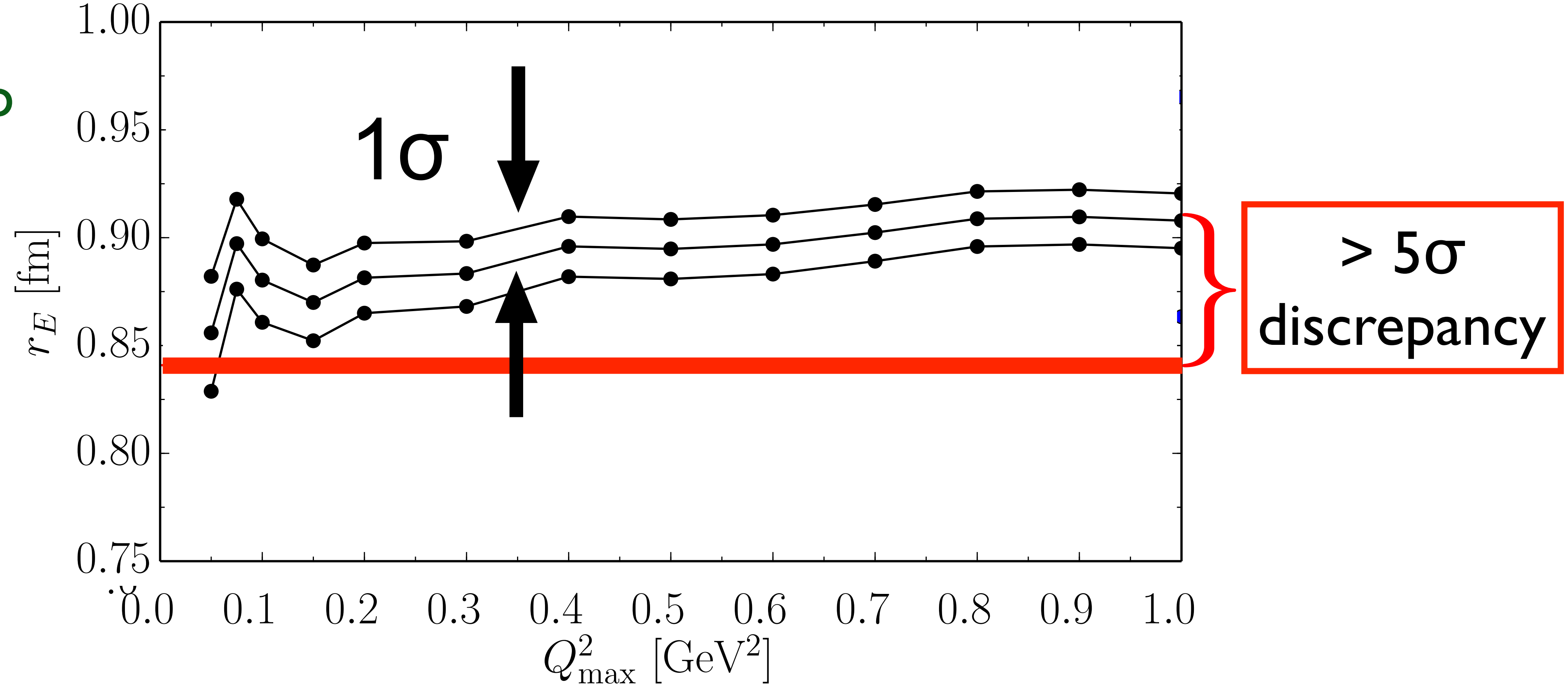

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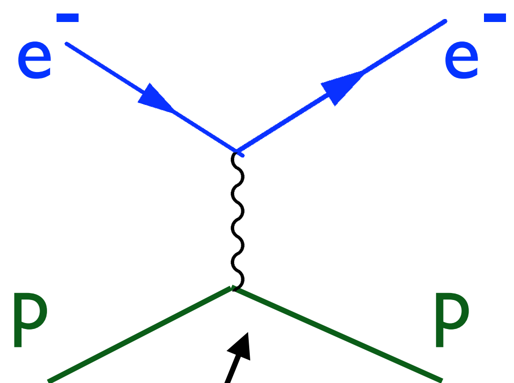
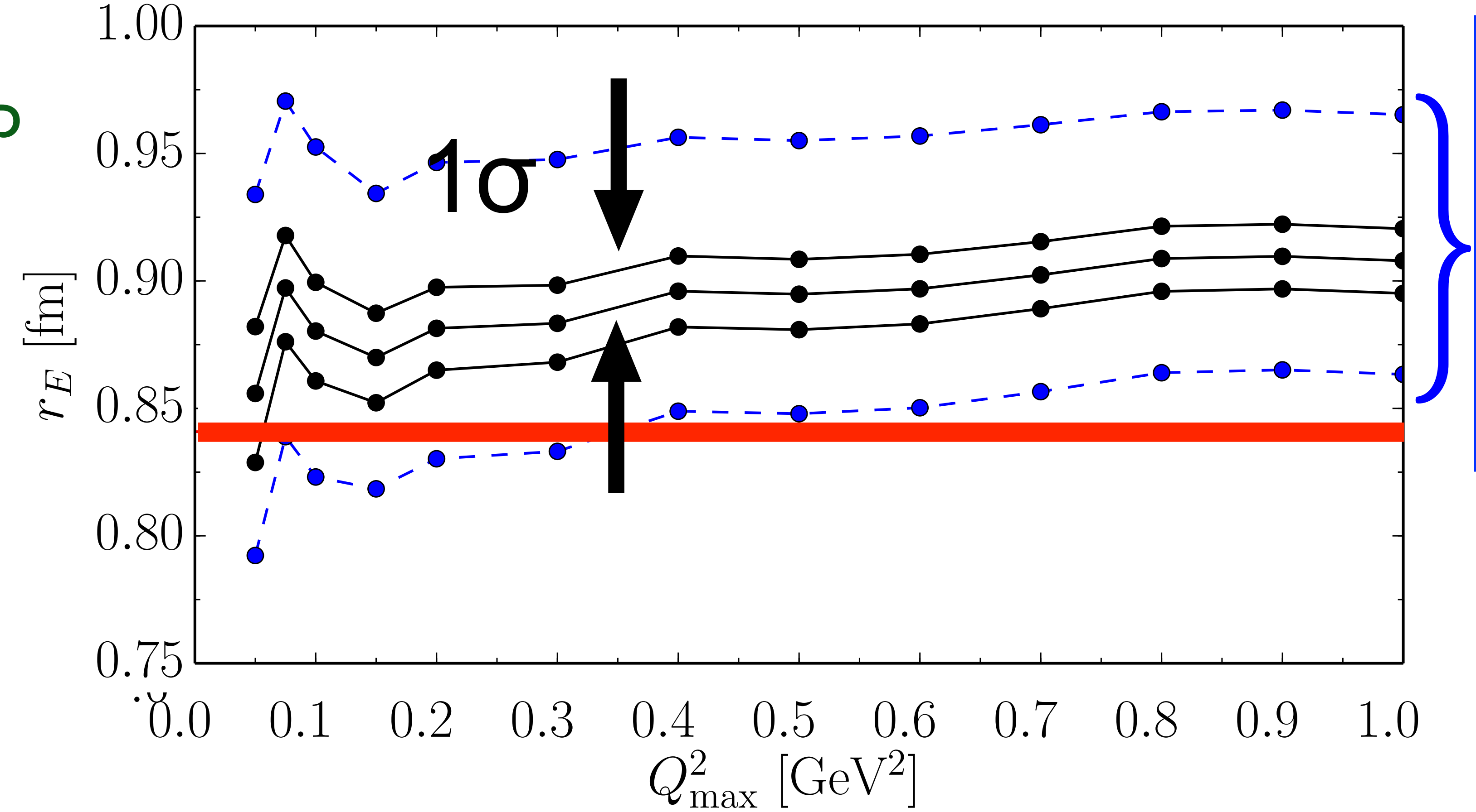


electric form factor

$$\frac{dF_E}{dq^2} \propto r_E^2$$



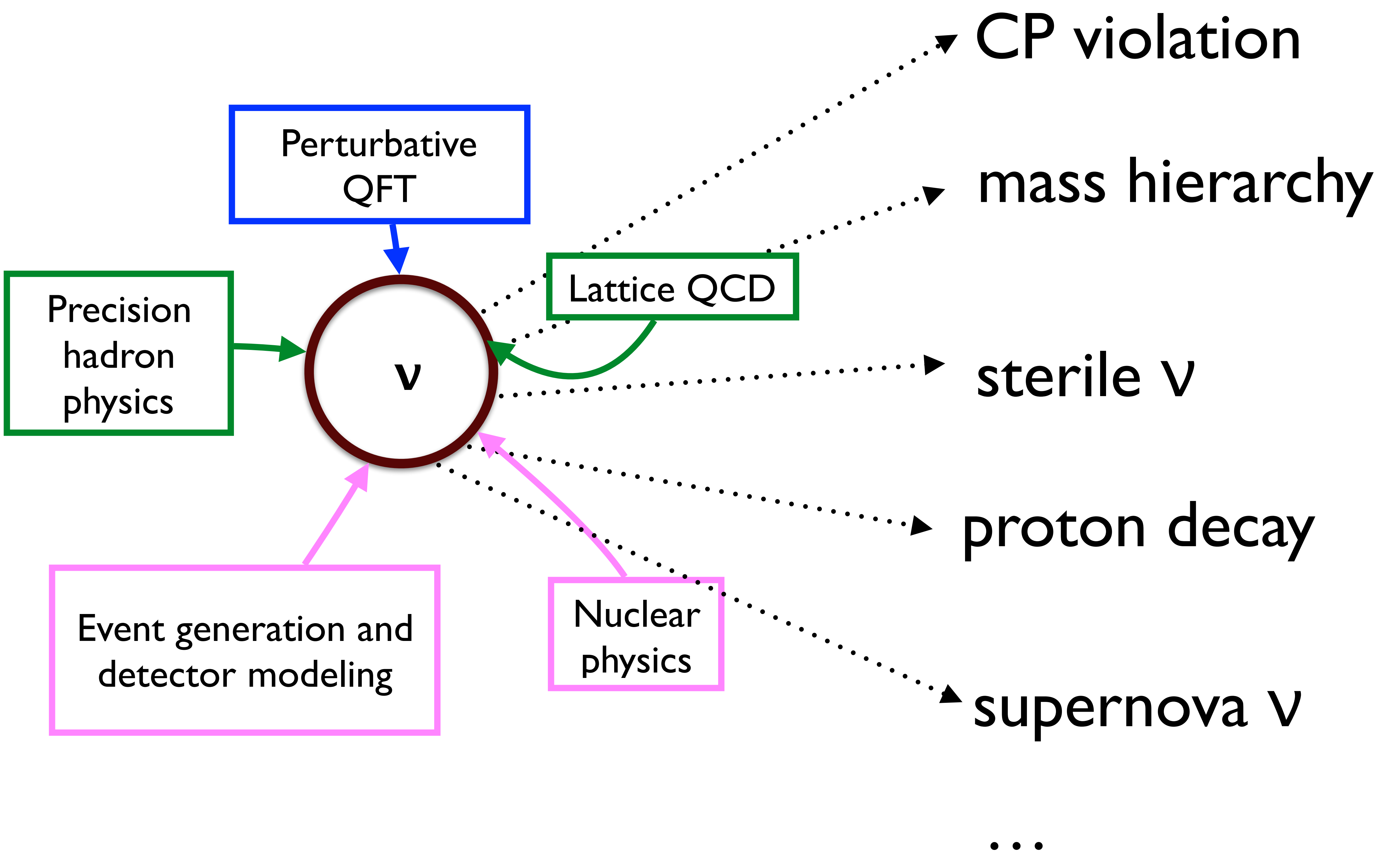
potentially large uncertainty from radiative corrections

- Unexpected Q^2 dependence of extracted radius, and potentially large radiative corrections

- Work in progress to implement complete radiative corrections

- For both e-p and ν-N: large logarithms upset naive perturbation theory (especially important for ν_e/ν_μ ratios)

QCD in many regimes critical to extracting fundamental physics in the neutrino sector



Cross sections key to discoveries in the neutrino sector

Particle theory has a critical role to play

- precision hadron physics: *model-independent amplitudes, error bars*

- radiative corrections: *critical for control over ν_e/ν_μ ratios, error bars*

- lattice QCD: *completely different systematics vs. elementary targets, error bars*

Important connections: other intensity frontier initiatives

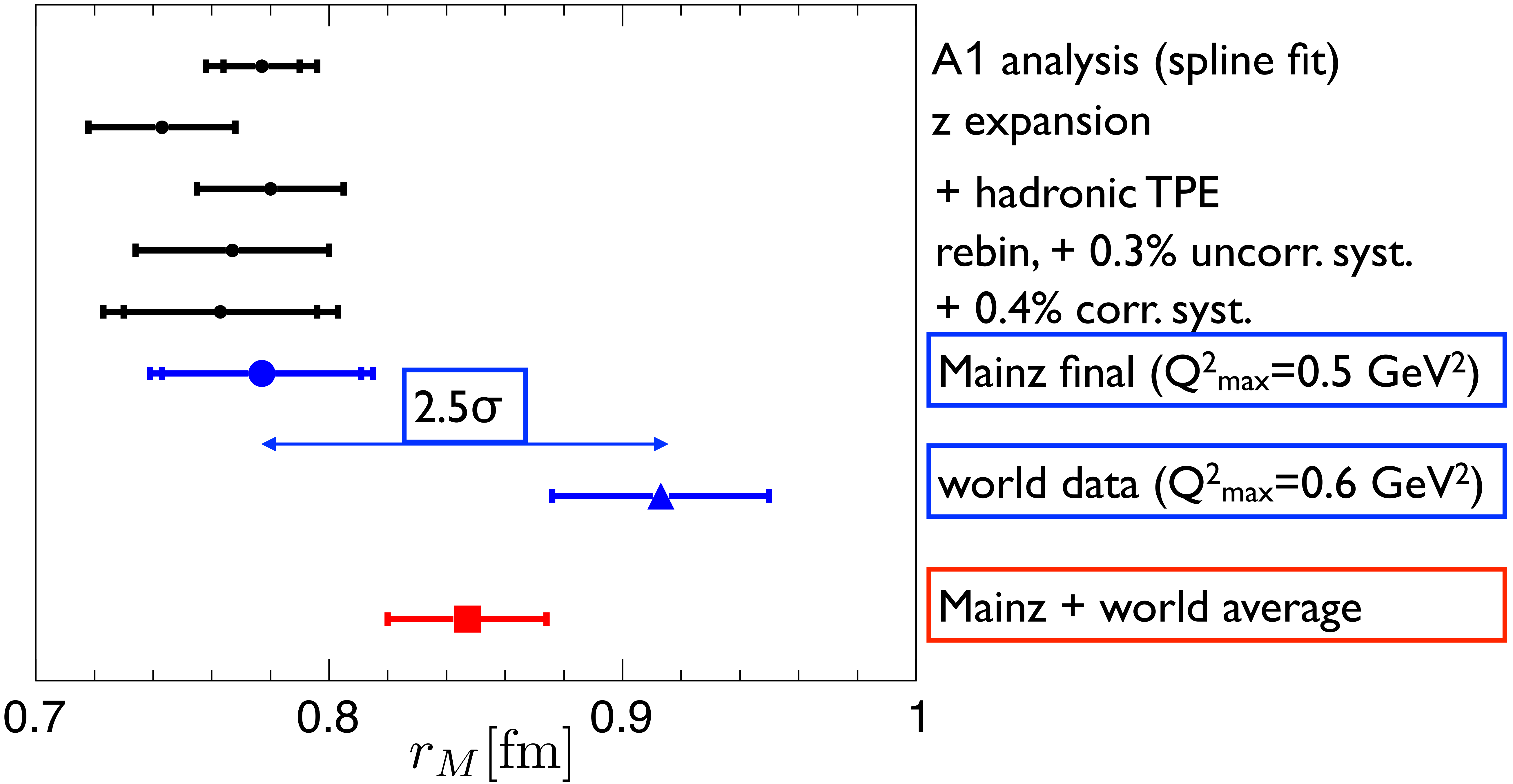
- radiative corrections: *neutrinos, g-2, proton radius puzzle, CKM, …*

- lattice QCD & baryons: *neutrinos, DM, proton radius puzzle, nEDM, …*

- interplay of nucleon amplitudes and nuclear effects: *energy reconstruction in ν-N scattering; atmospheric bkgd. to proton decay, next generation WIMP searches, neutrinoless double beta decay, …*

back up

Proton magnetic radius

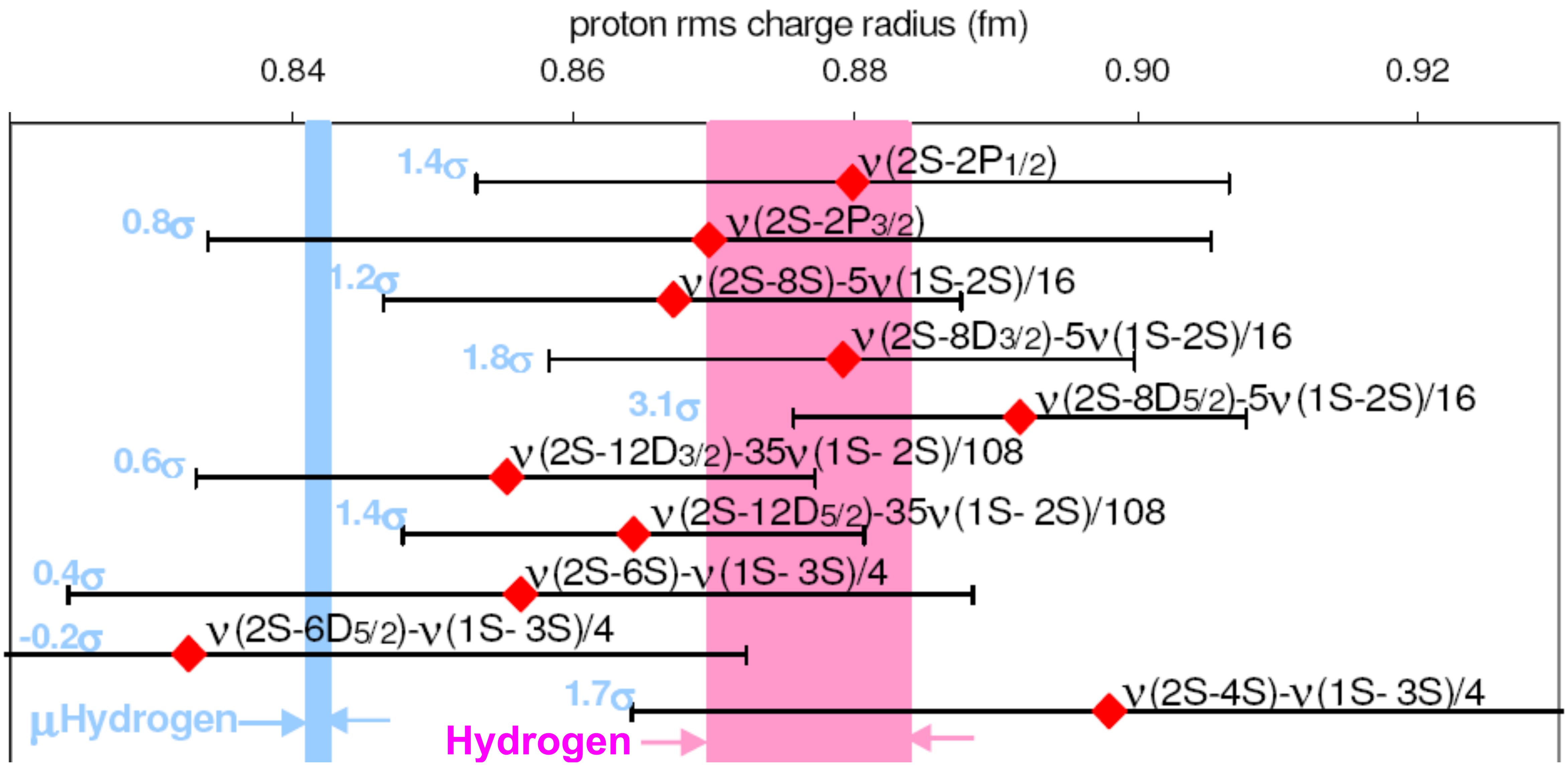


r_M^{Mainz} = 0.777(34)(17)

r_M^{world} = 0.913(37)

simple average: $r_M^{avg.}$ = 0.847(27)

Experimental landscape: hydrogen



plot courtesy E. Hessels, proton radius workshop 2014

- no straightforward systematic explanation identified, but ~5σ deviation results from summing many ~2σ effects